The aerosol optical depth by components from the Multiangle Imaging SpectroRadiometer (MISR)

: applications to evaluating chemistry transport models and studying optical properties of wildfire-induced aerosols

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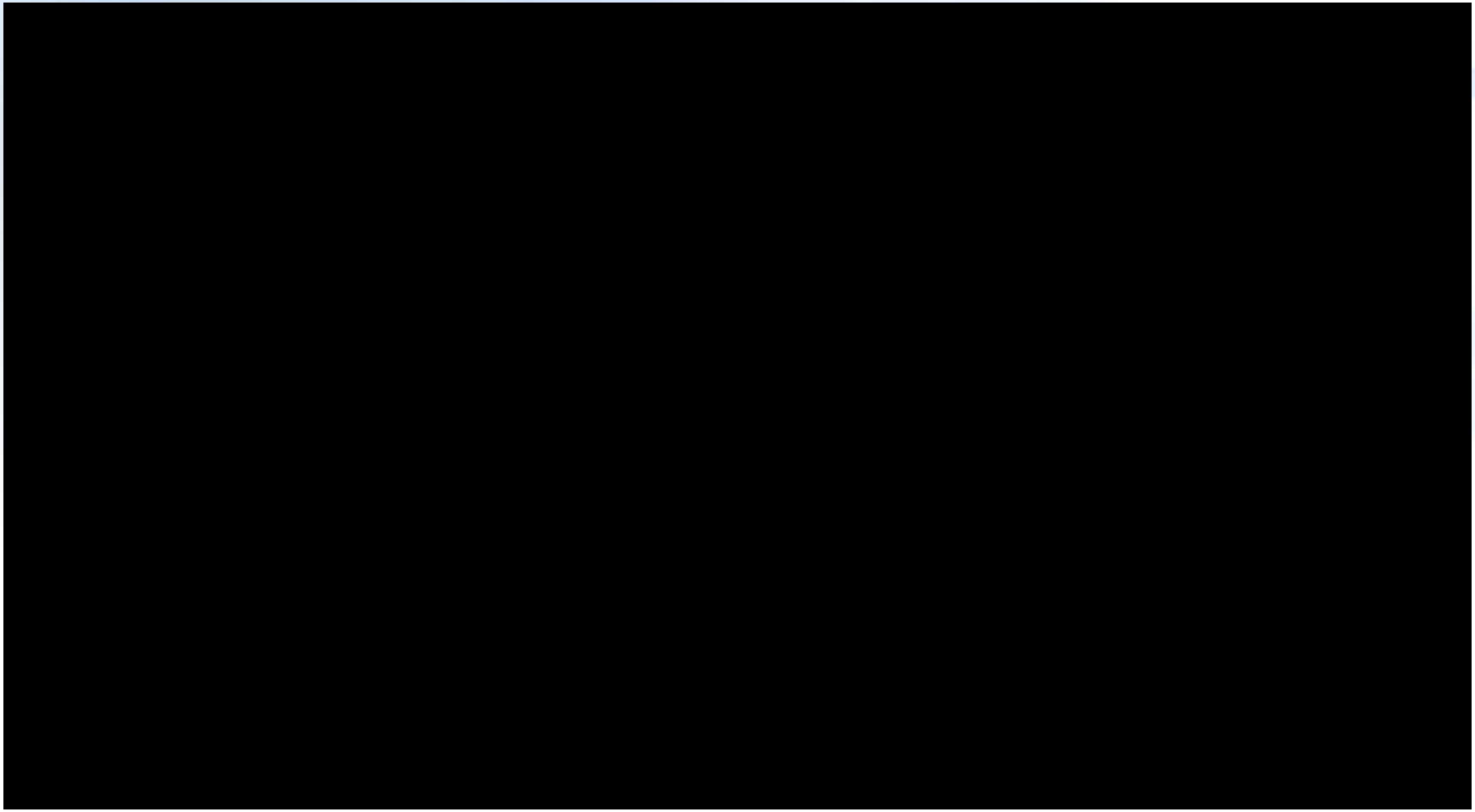
Outline

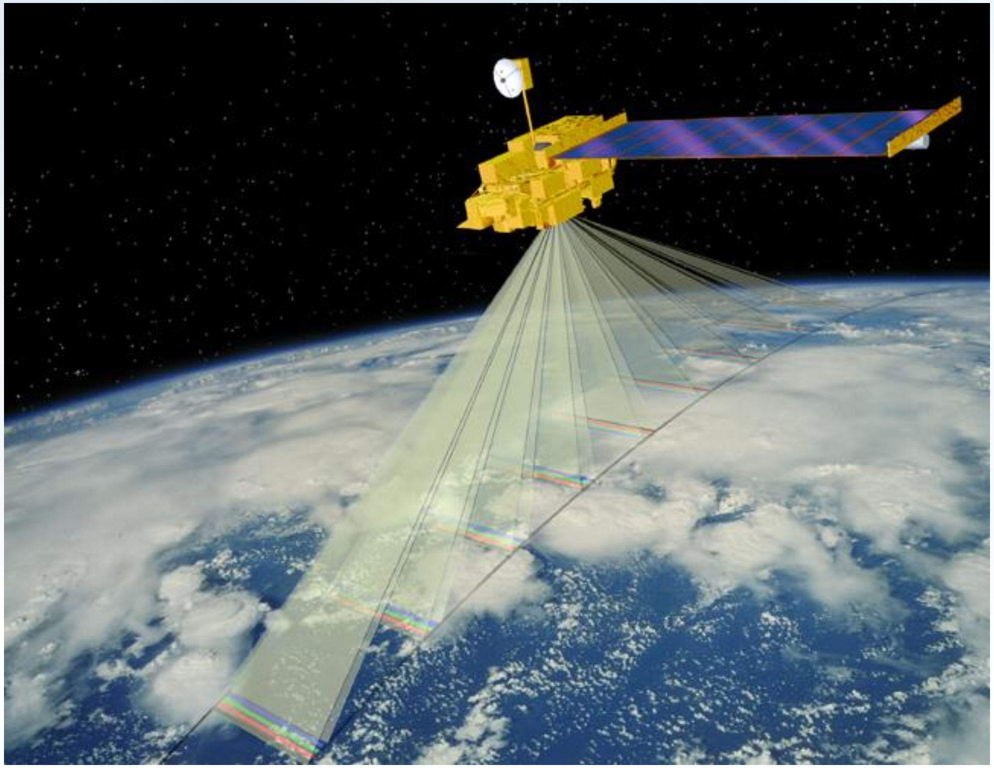
- Introduction
  - Multi-angle Imaging SpectroRadiometer (MISR)
  - MISR Joint Aerosol (JOINT_AS) Product
- Comparison of MISR Joint Aerosol Product with simulations from chemistry transport models
- Stability in the climatological aerosol optical depth by components
- Optical properties of wildfire-induced aerosols
- AirMSPI and MAIA: towards the aerosol observation of the future

NASA Terra Satellite
[March 2000 – present]



courtesy of Prof. Di Girolamo at Univ. of Illinois

Multi-angle Imaging SpectroRadiometer (MISR)



Nine view angles at Earth surface:
70.5º forward to 70.5º backward

Nine 14-bit pushbroom cameras

275 m - 1.1 km sampling

Four spectral bands at each angle:
446, 558, 672, 866 nm

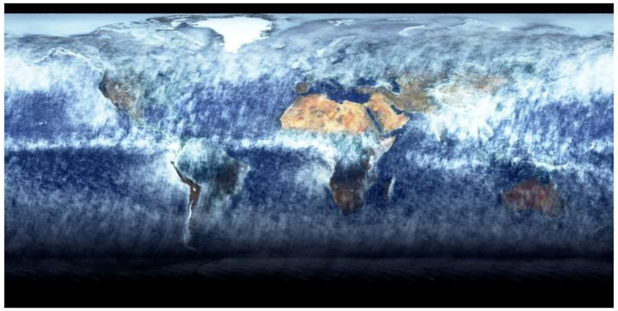
400-km swath: 9-day coverage
at equator, 2-day at poles

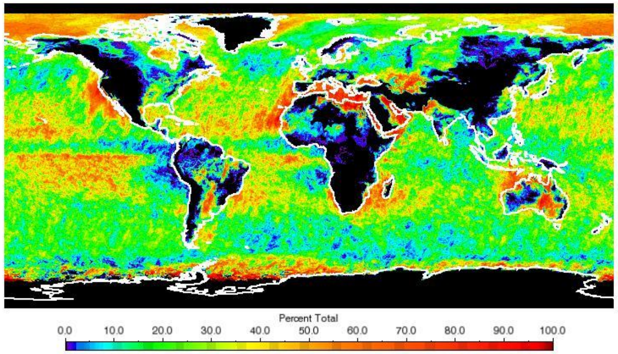
7 minutes to observe each scene
at all nine angles

courtesy of Michael Garay at JPL

Example MISR Standard Products

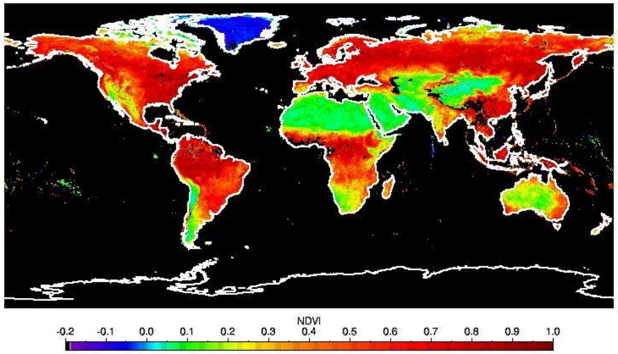
Radiance

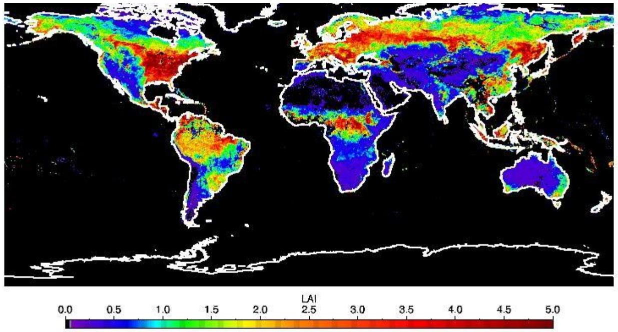




Cloud Top Height

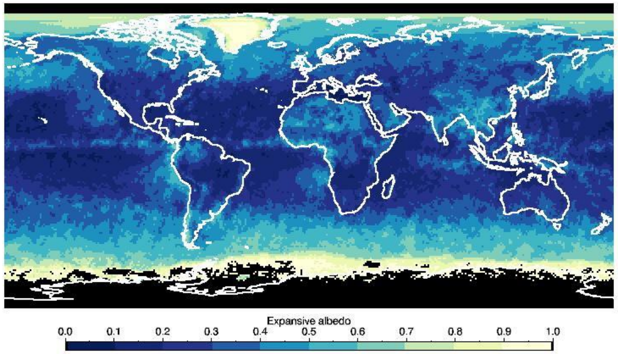
NDVI (normalized difference vegetation index)

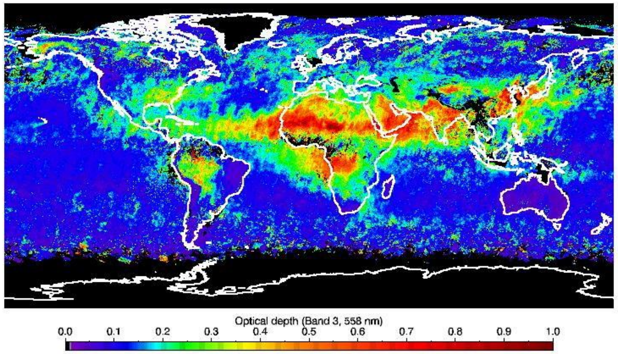




LAI (leaf area index)

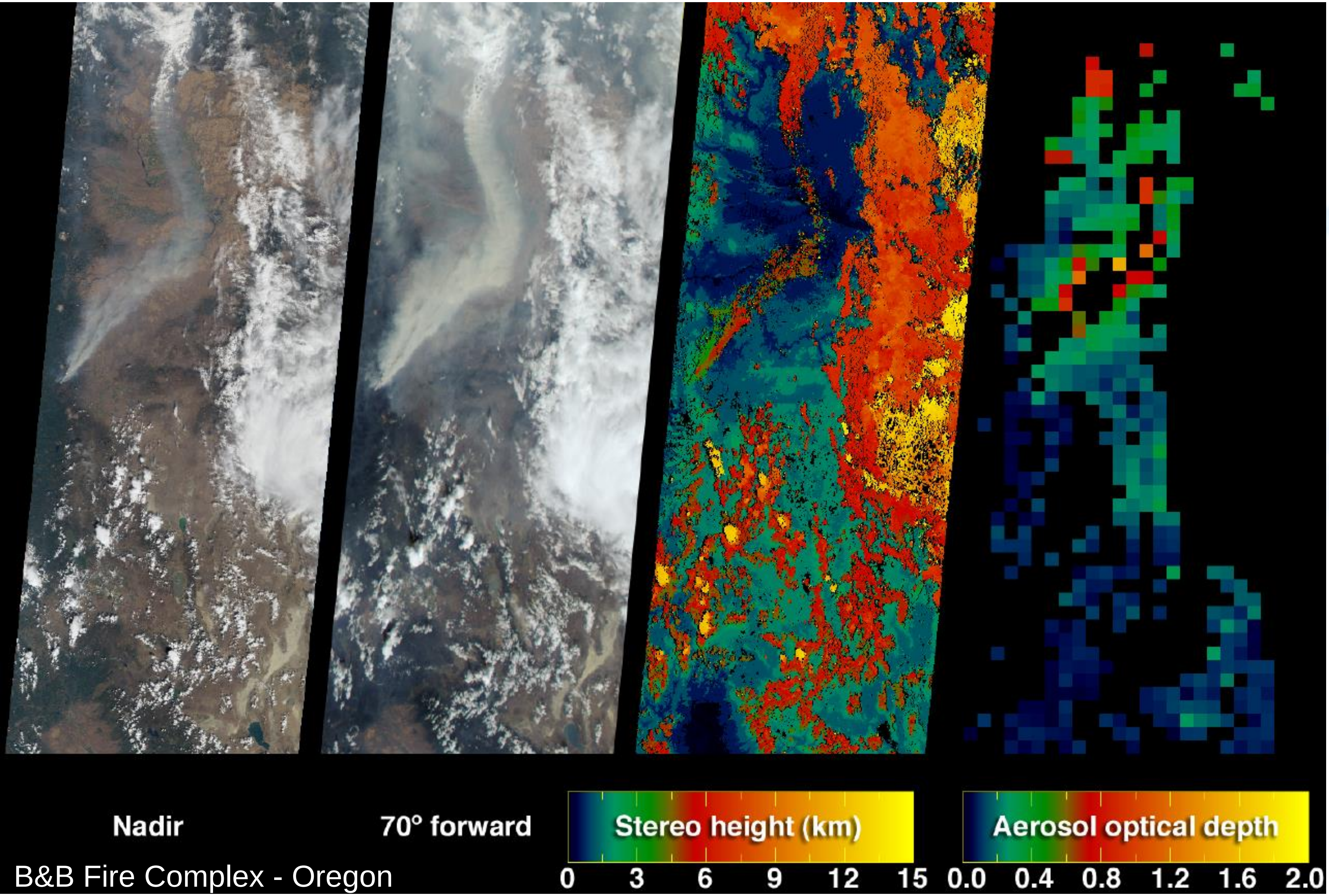
Albedo





AOD (aerosol optical depth)

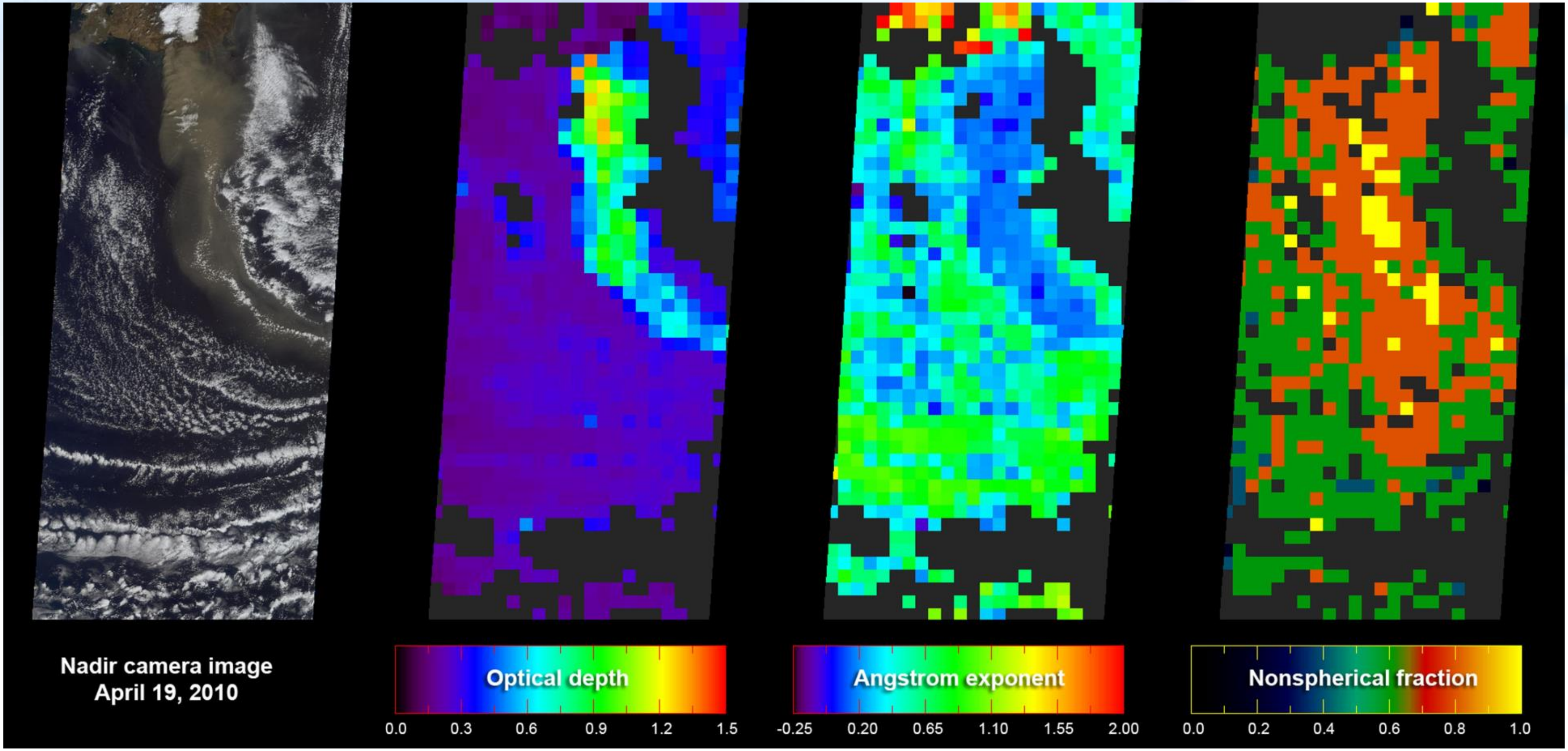
courtesy of Michael Garay at JPL



B&B Fire Complex - Oregon

courtesy of Michael Garay at JPL

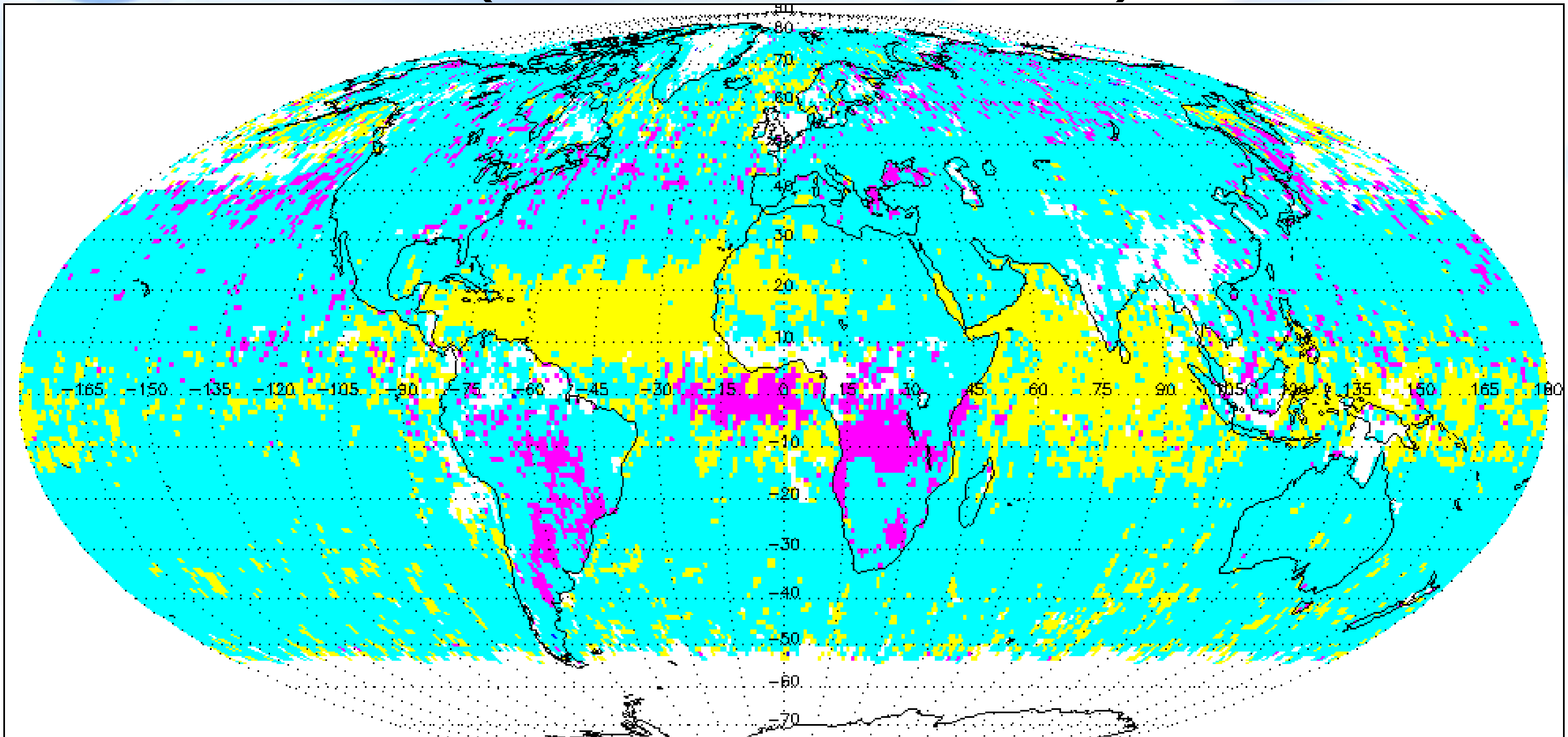
Aerosol particle properties from MISR



MISR views of Eyjafjallajökull – 4/19/2010

courtesy of Michael Garay at JPL

74 Aerosol Mixtures (Standard Product)



Kahn and Gaitley (2015)

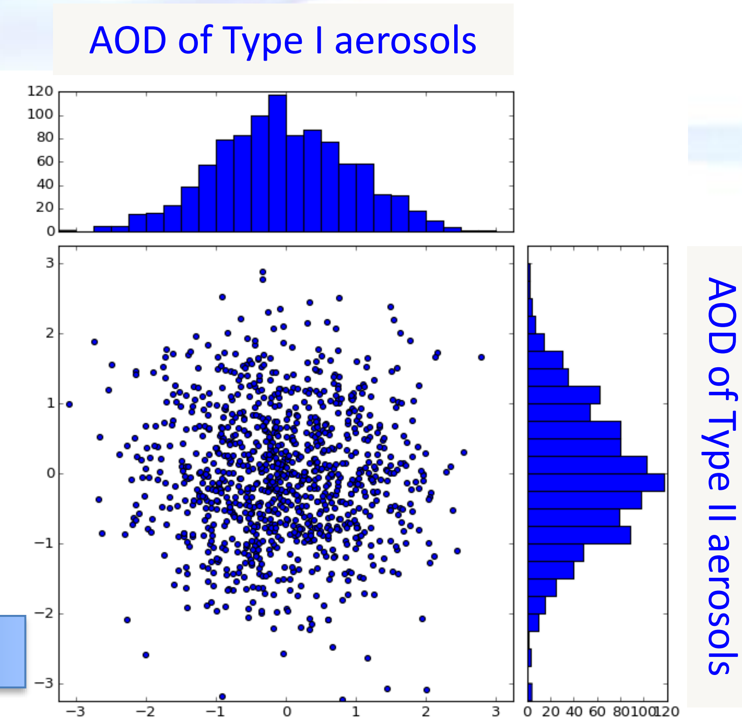
Key

Spherical Non-Absorbing	Spherical Absorbing + Non-Spherical (Tie)
Spherical Absorbing	Spherical Non-Absorbing + Non-Spherical (Tie)
Non-Spherical	Spherical Absorbing + Spherical Non-Absorbing (Tie)

MISR L3 Joint Aerosol (JOINT_AS) :

algorithms based on *Braverman and Di Girolamo*, (2002)

- Global statistical summaries of MISR Level 2 AOD: 8-dimensional histograms.
- Resolution: 5 x 5 degrees (60 S – 60 N) & monthly



mean, standard deviation*, skewness* and extreme values*

- The size of data files is significantly reduced from the Level 2 data, while approximating key information (marginal distributions and approximate moments of 8 aerosol types).

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  - *Lee et al.* (2016), Climatology of the aerosol optical depth by components from the Multi-angle Imaging SpectroRadiometer (MISR) and chemistry transport models, ACP.
  - *Lee* (2016). AOD_monthly_2000-MAR_2016-FEB_from_MISR_L3_JOINT.nc, https://doi.org/10.6084/m9.figshare.3753321.v1
- Stability in the climatological aerosol optical depth by components
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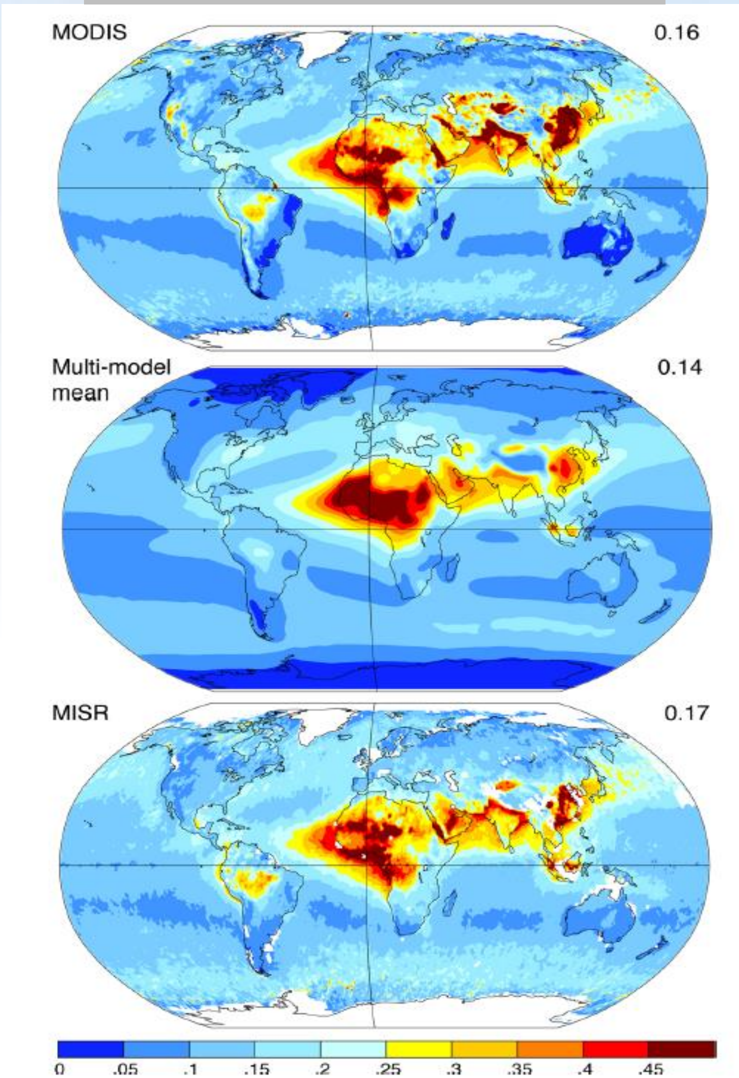
Motivation

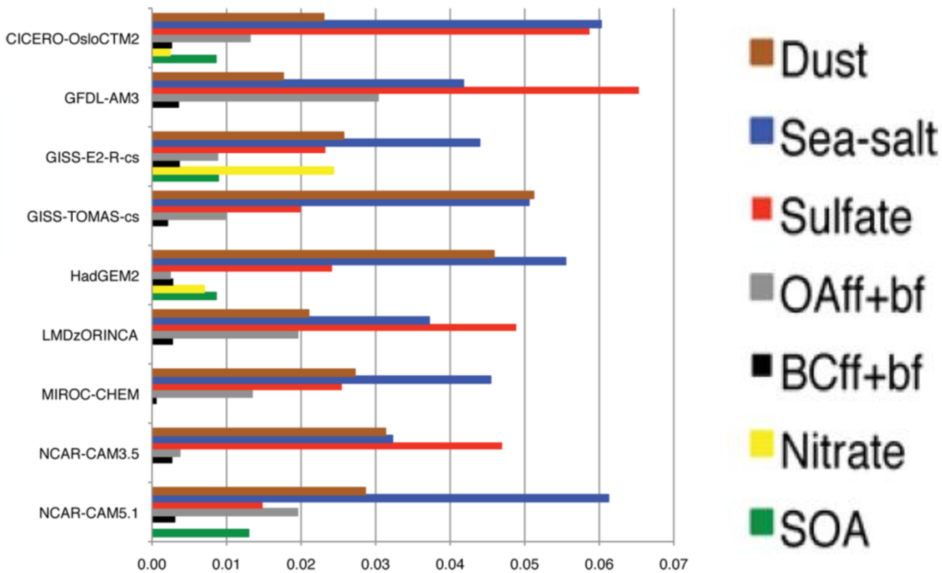
Shindell et al. (2013), Radiative forcing in the ACCMIP historical and future climate simulations

Total Aerosol Optical Depth (AOD)



- Total aerosol optical depth (AOD) from satellite observations (MISR, MODIS and so on) has been widely used to evaluate and constrain chemistry climate models (CCMs).
- However, chemistry model simulations show considerable spread in AOD by component.
- MISR provides **AOD for different aerosol types** that has potential to constrain and improve CCMs.

AOD by component



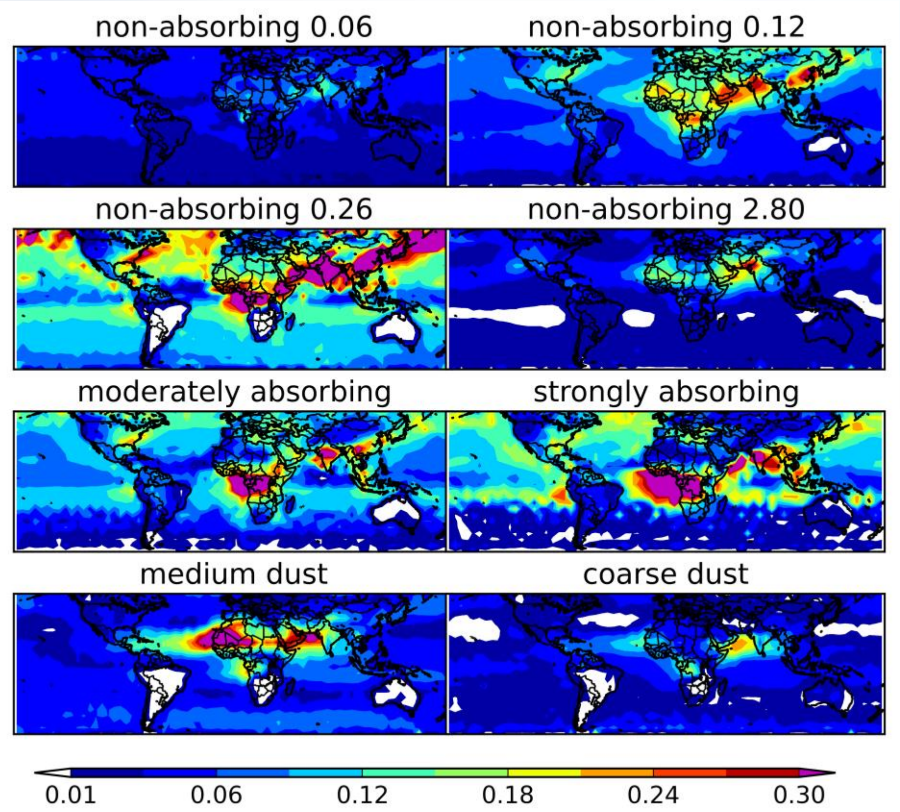
Objectives

- What is the added value of using AOD from MISR?
  - Investigate if multi-year MISR climatology of AOD by component could be used for evaluating CCMs.
  - Evaluate AOD for different aerosol types in CCMs by comparing multi-year MISR climatology.
- Why do we need information about AOD distributions other than averaged AOD?
  - Evaluate (and correct if possible) potential biases and outliers in MISR by examining characteristics of marginal distributions for each MISR aerosol type's AOD in various regions of interests.

MISR (July 2000-2013)

- 8 types:

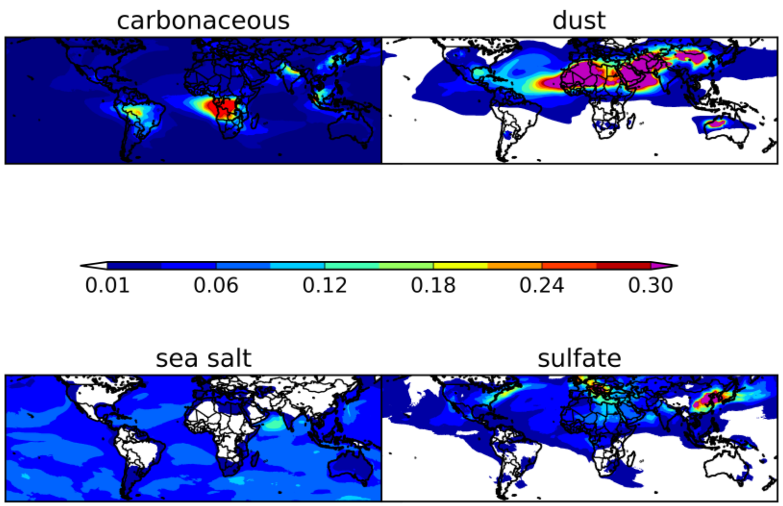
spherical nonabsorbing (4 sizes), spherical absorbing (small or large SSA), nonspherical (2 sizes)



NICAM (July 1-8, 2006)

- 4 types:

carbonaceous, dust, sea salt, sulfate

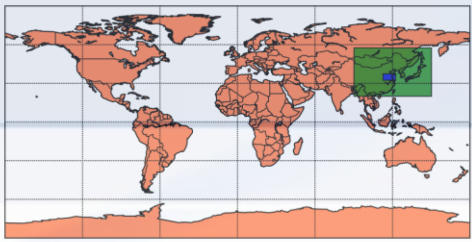


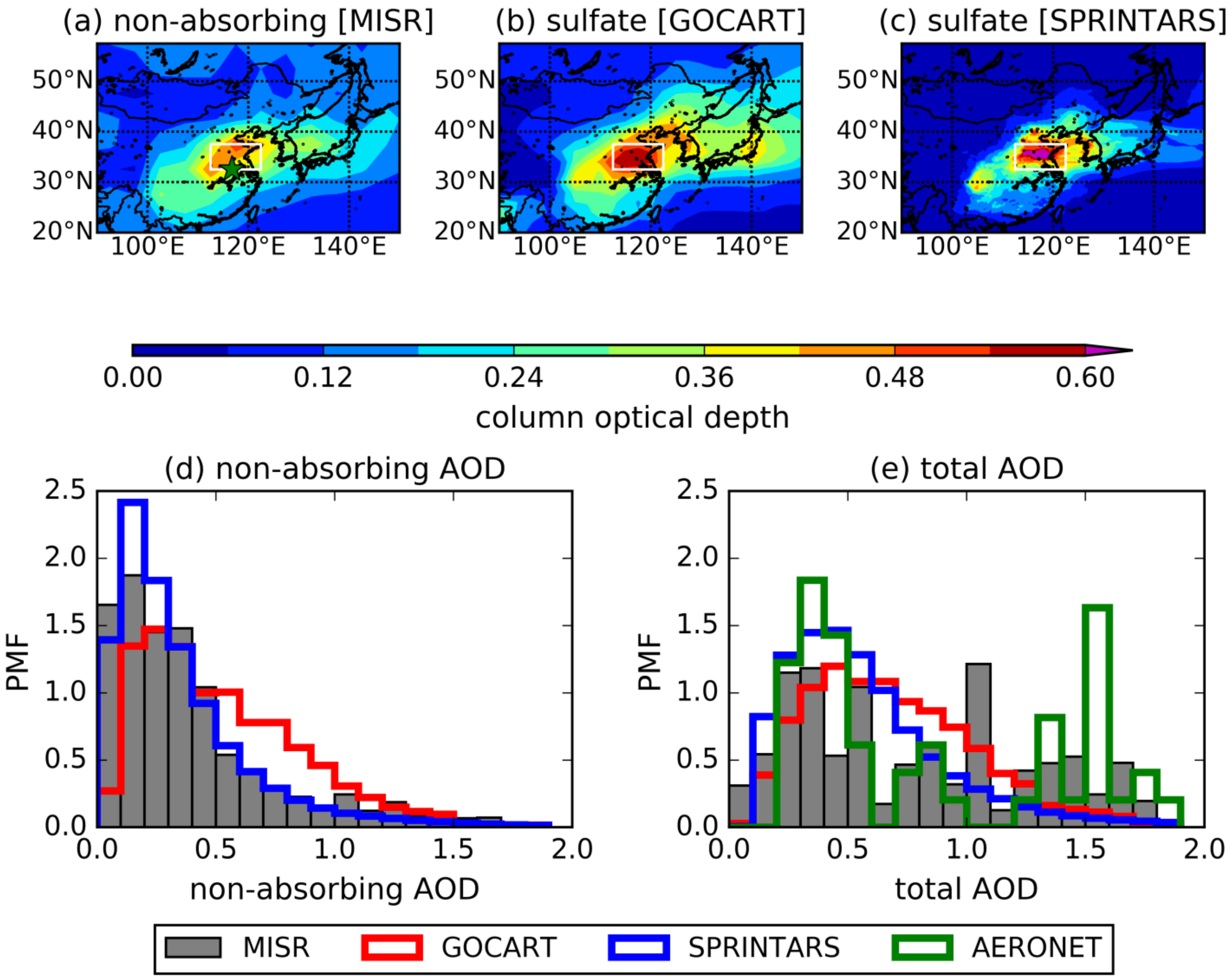
How to compare the 8 types in MISR and aerosol types in models?

AOD in MISR	AOD in models
absorbing aerosols (SSA 0.8 + SSA 0.9)	carbonaceous aerosols (od550bc+od550oa)
non-spherical aerosols	dust (od550dust)
non-absorbing aerosols	sulfate aerosols (od550so4)

Single scattering albedo (SSA) = (scattering)/(scattering + absorption)

East Asia [July]

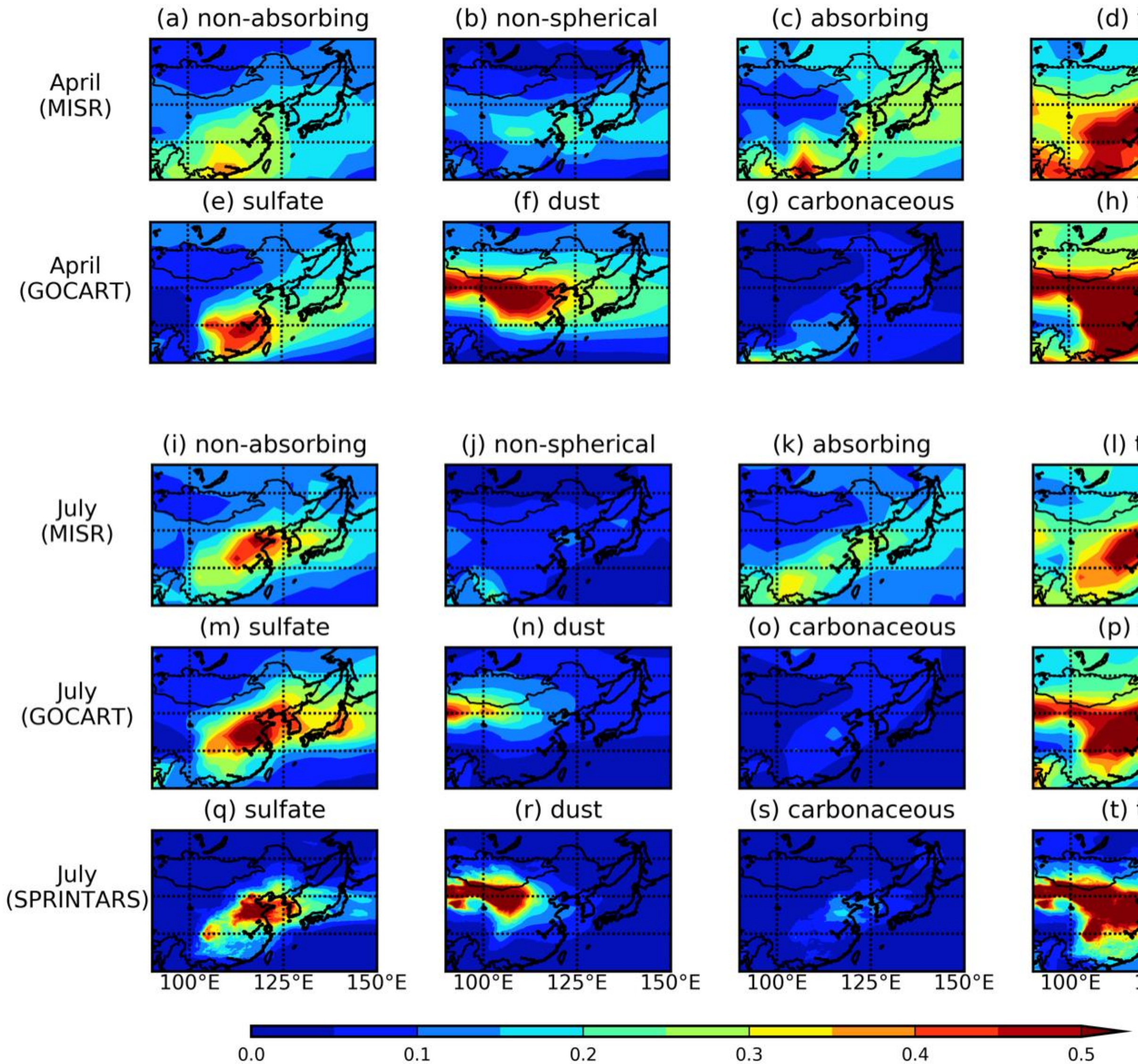




- Dominant type: nonabsorbing (sulfate)
- The observed distributions of total AOD do not follow the log normal distribution.

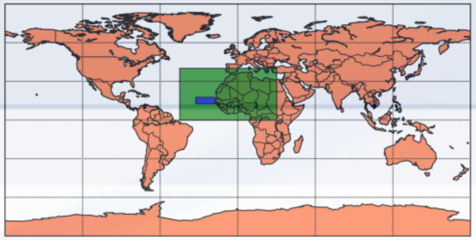
Aerosol Robotic Network (AERONET)

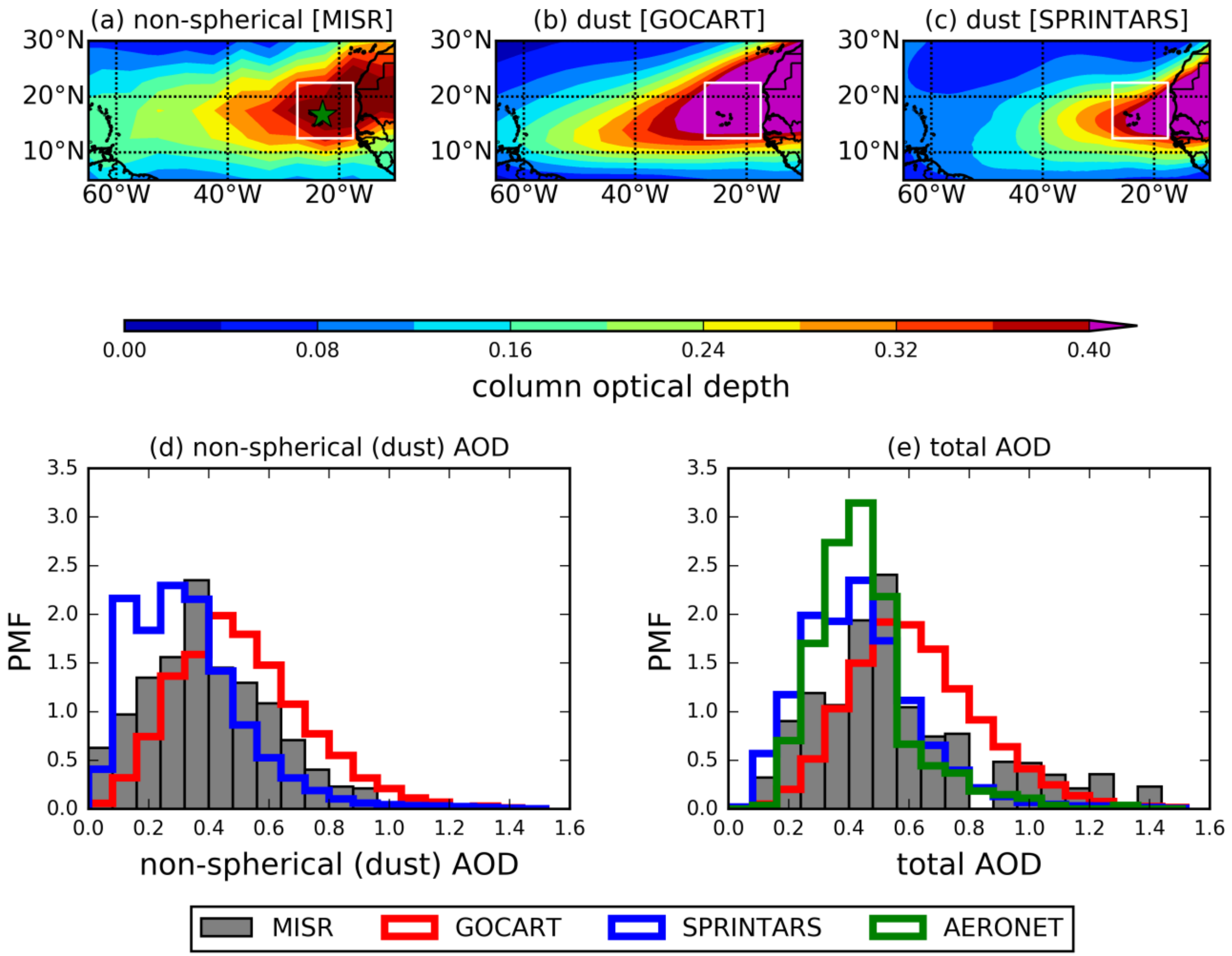
East Asia [April vs. July]



- The dominant sources of aerosols are different.
- MISR's non-spherical AOD in April

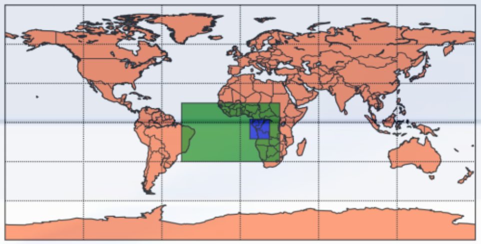
Eastern Atlantic [July]

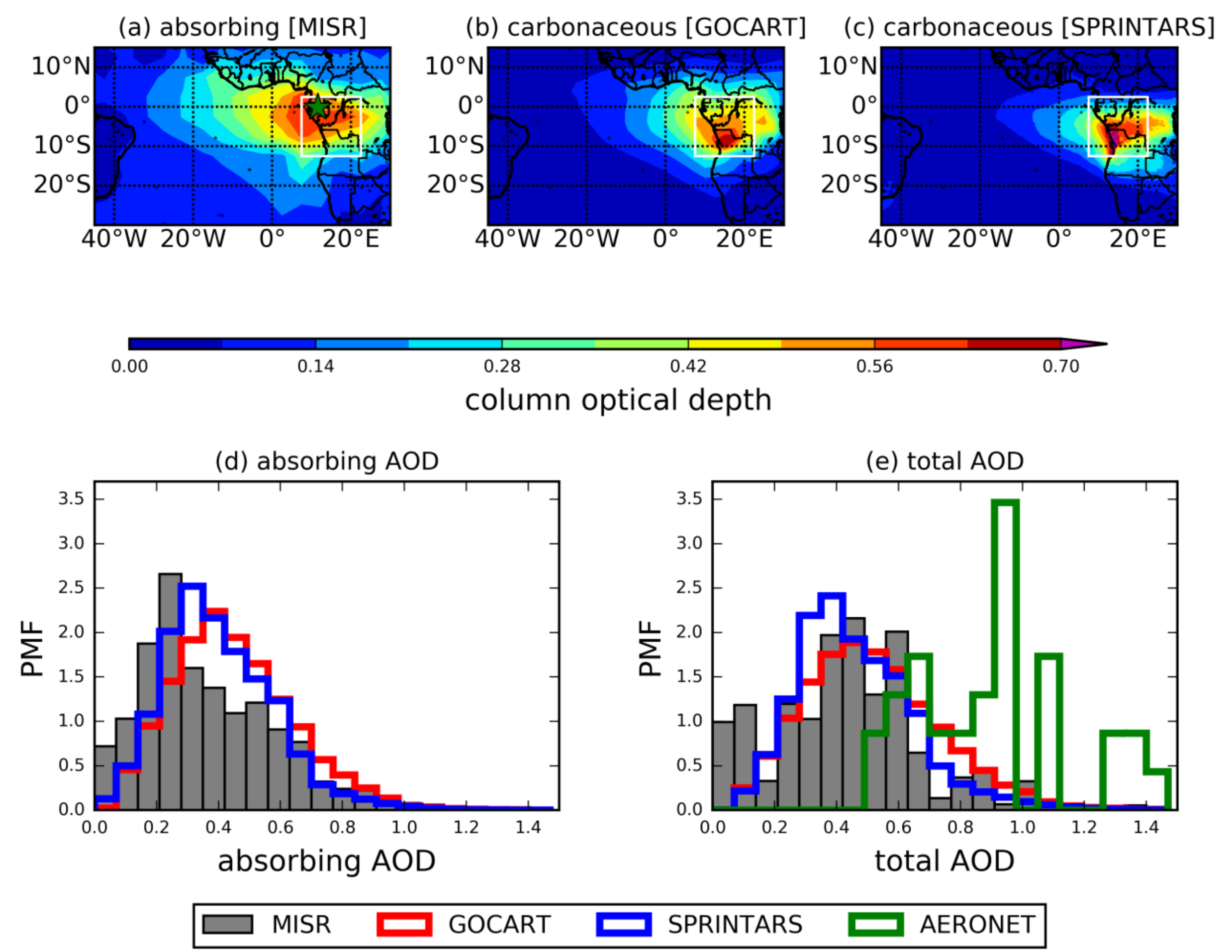




- Downwind from the largest source of dust aerosols on Earth
- Both nonspherical and total AOD in the region show good agreement with the simulated AOD.

Central Africa [July]





- Massive emissions of carbon aerosols are dominated by savanna and grassland fires.
- Despite the difference between MISR and the models, MISR's absorbing and total AODs over a longer period than the AERONET station provide a powerful model diagnostics.

Summary: part I

- MISR Level 3 Joint Aerosol product provides monthly climatological moments (mean, standard deviation, skewness and so on) of AOD for 8 different aerosol types.
- **The combined AOD of MISR aerosol types is comparable to simulated AOD** of non-absorbing (sulfate + nitrate), absorbing (BC + OA) AOD and dust AOD in chemistry transport models and chemistry climate models.
- In the three high-AOD regions studied, we show how the reliance on a single, dominant aerosol type can be inappropriate for certain locations and seasons.

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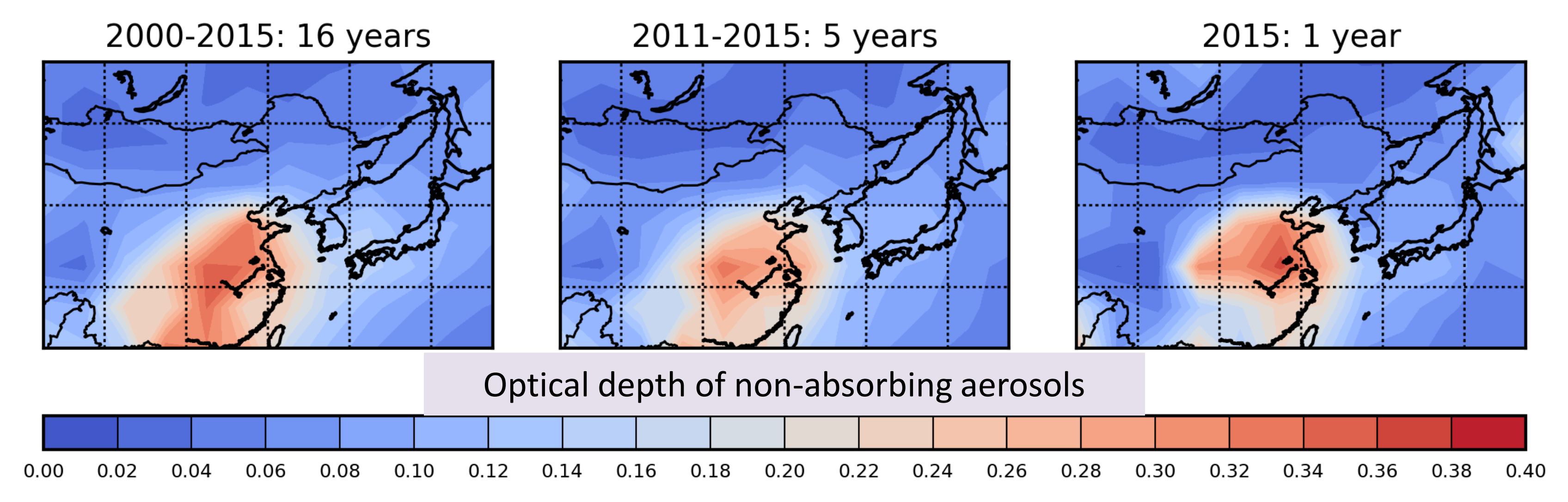
- Stability in the climatological aerosol optical depth by components
  - Lee et al., Evaluation of stability in the climatological aerosol optical depth by components from MISR for assessing applicability in benchmarking climate models, under review.
- Optical properties of wildfire-induced aerosols
- AirMSPI and MAIA: towards the aerosol observation of the future

Why do we care about the length of AOD observations?

- WMO standards require at least 30 years of observations without data gaps to define climatology for a variety of climate applications.
- NASA's Earth Observing System (EOS) satellites have provided unique AOD observations to study the Earth system over the last 16+ years.
- The chemistry models participating in the Aerosol Comparisons between Observations and Models (Aerocom) have substantially improved their capabilities in modeling aerosols. However, there remains uncertainty in both satellite observations used as reference datasets and AEROCOM model simulations even when we compare climatological AOD between the observations and models.

Objectives

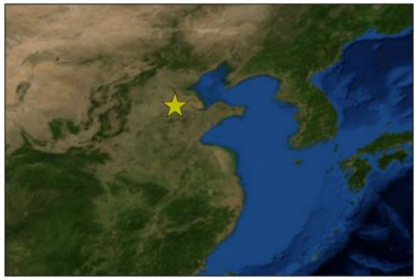


- Are the 16 years of MISR measurements enough to build AOD climatology?
  - ✓ Quantify the impact of the length of observations on climatological mean AOD: measure stability of the AOD climatology.
- How do the Aerocom models simulate optical depths for different types of aerosols?
  - ✓ Evaluate the climatological seasonal cycle of AOD in the models.

Uncertainty of the multi-year mean AOD due to temporal subsampling

- Subsample the 16 seasonal means (September-October-November, SON) between 2000-2015 without replacement 100 times => 100 multi-year means of AOD

SON mean AOD over the 16 years: 0.362

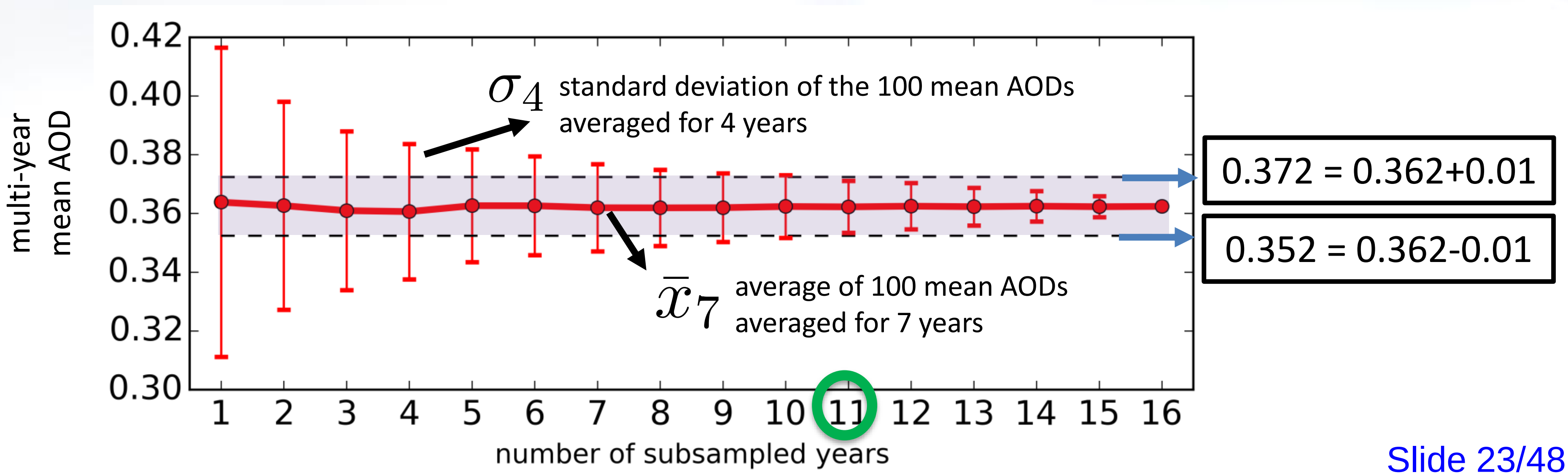


for sample_size (n) = 1, 15 # years

for number_sample = 1, 100 # random subsets

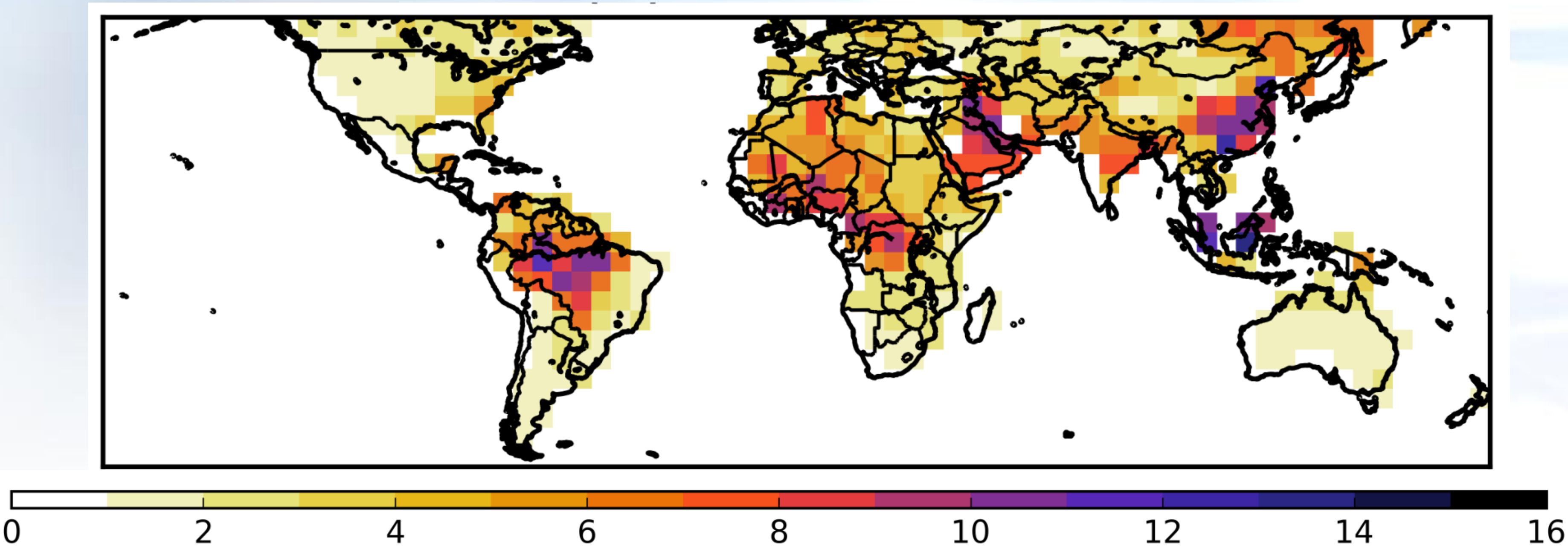
sub_climatology[ ] = CALC_MULTI_YEAR_CLIM( )

ex) for *n*=4, (2002, 2003, 2005, 2015) (2004, 2007, 2008, 2009).. (2002, 2003, 2004, 2015)



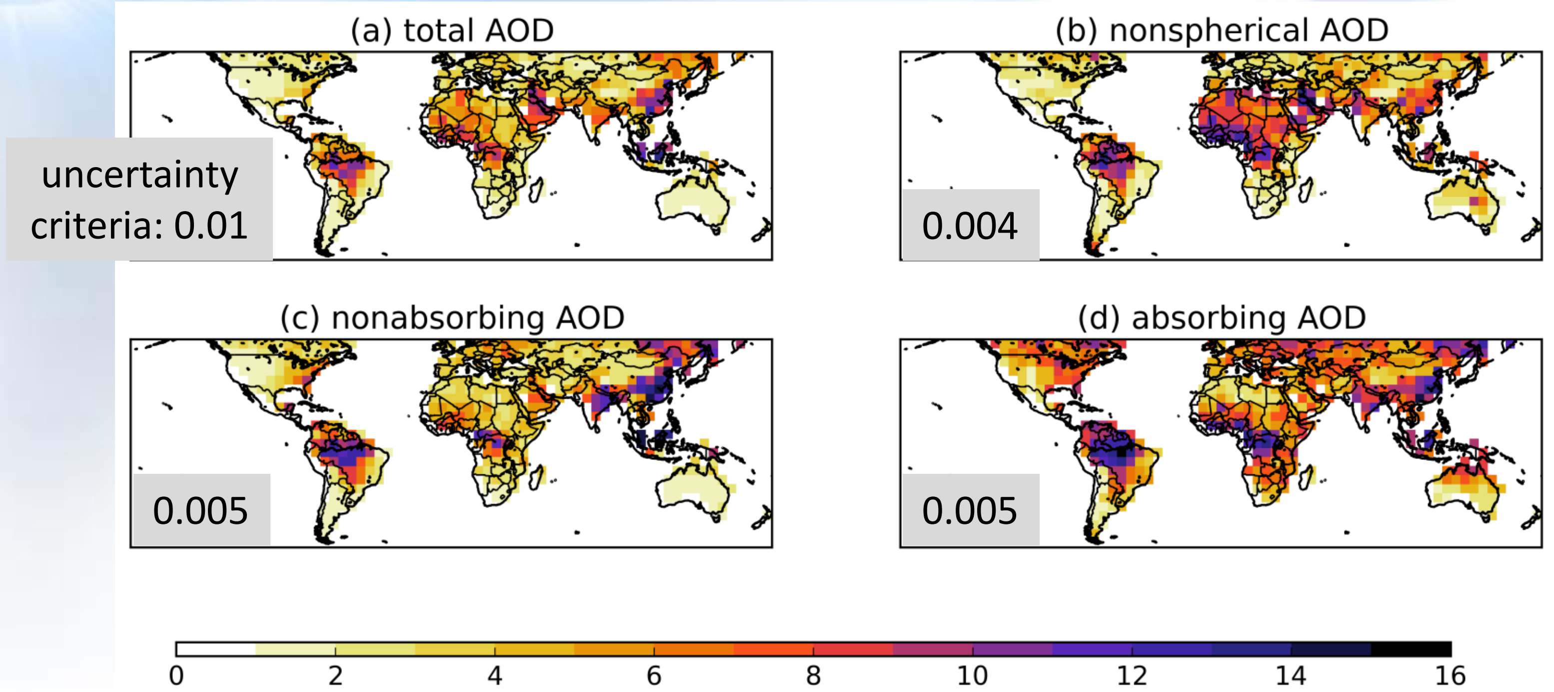
clim. AOD-0.1 < $\bar{x}_n \pm \sigma_n$ <clim. AOD +0.1

minimum # of years required to calculate climatological total AOD (annual mean) with the accuracy of 0.01



- Conversion of interannual variability in AOD into another quantity useful for studying climatology
- Overall, the 16-year observation record is valuable to define climatological AOD.
- In some regions (e.g. Amazon and Maritime continent), 16 years may not be long enough to build the climatology of annual mean AOD.
- Evaluation of simulated AOD needs to be done for the maximum overlap periods between observations and models.

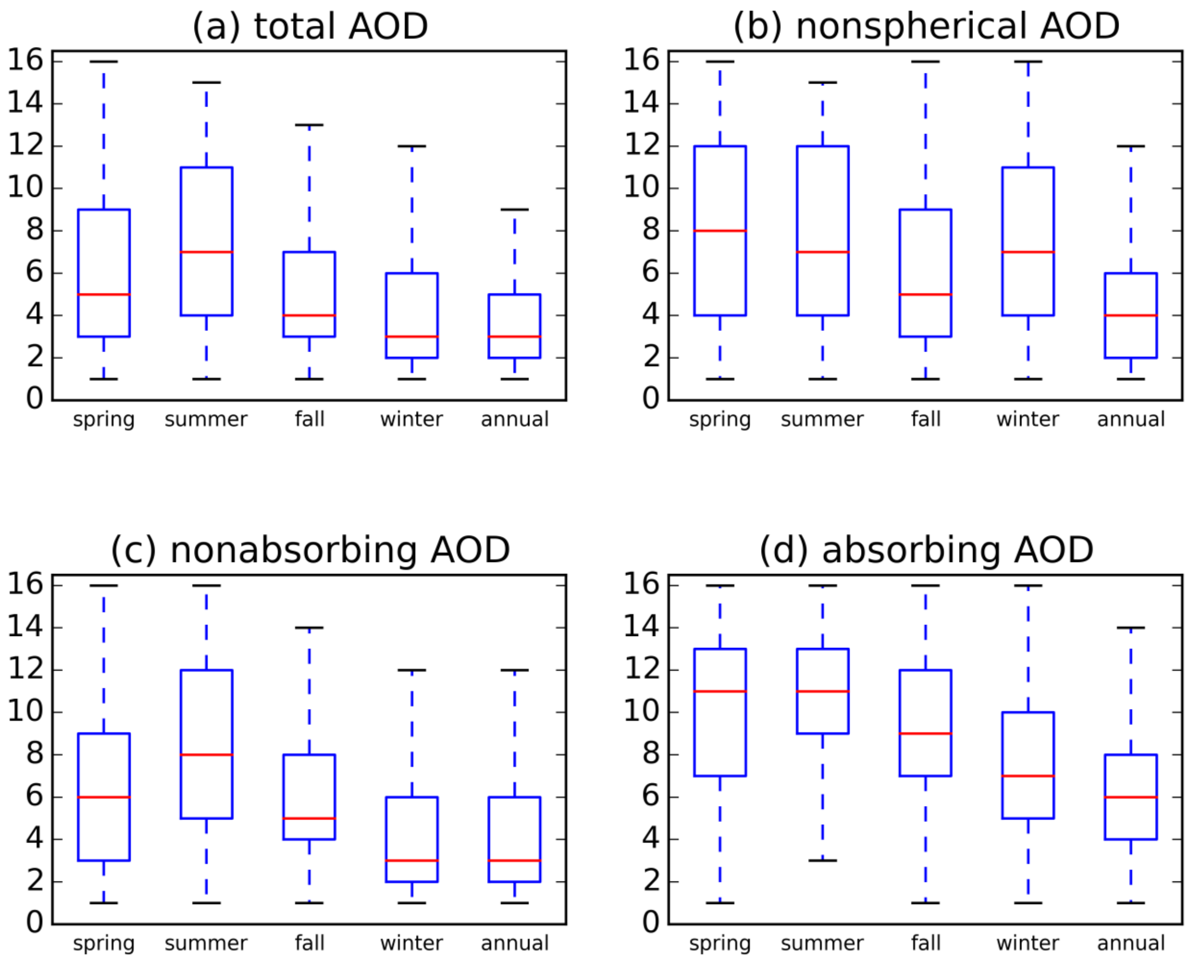
Stability of the multi-year mean AOD by component



- The uncertainty of multi-year mean optical depth due to temporal subsampling becomes large when generating climatological AOD by components, especially for non-spherical and absorbing AOD.
- The uncertainty is considerable in major sources of aerosols (e.g. the Sahara Desert, Amazon, and Central Africa).

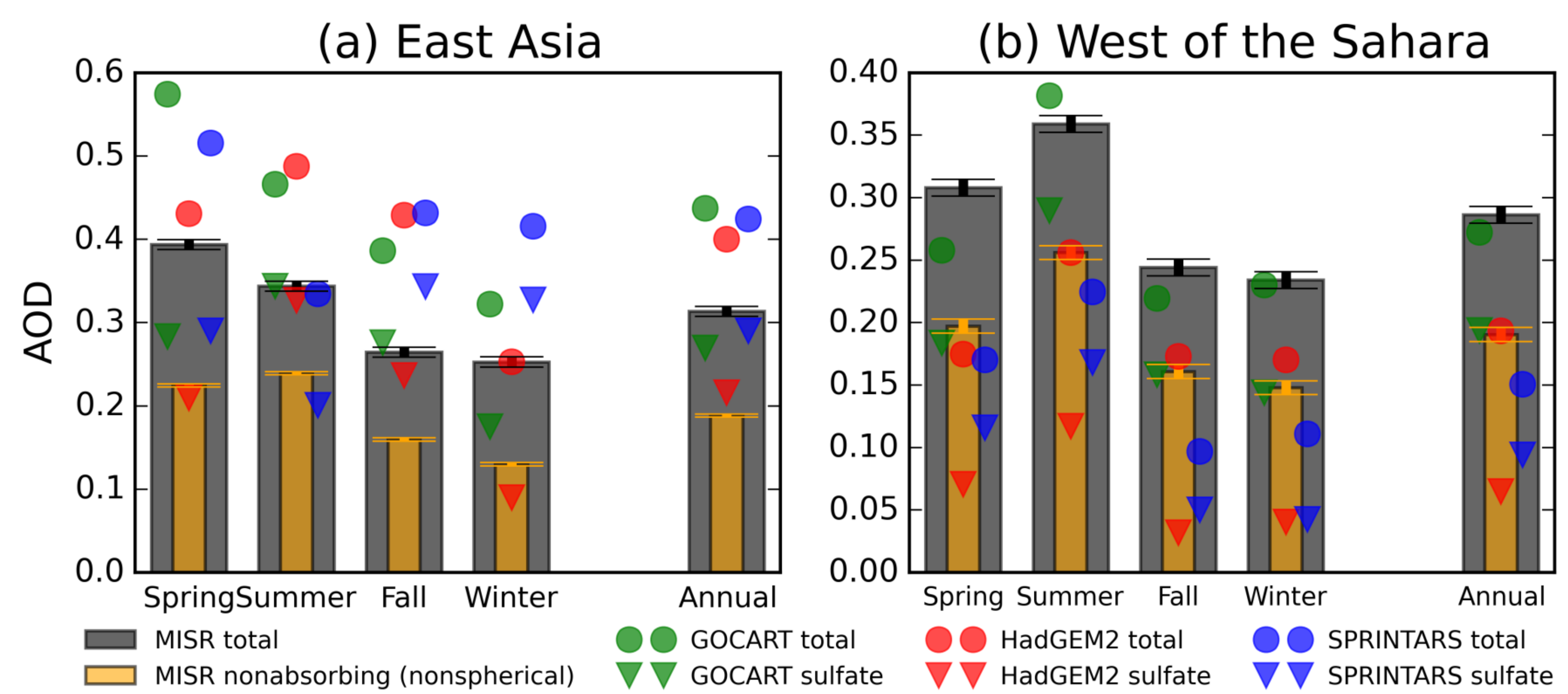
How long is long enough to define stable climatological AOD?

The global median of the minimum years required to obtain the sample standard deviation less than the predefined accuracy levels (0.01 for total AOD, 0.004 for nonspherical AOD, and 0.005 for nonabsorbing and absorbing AOD) for each season and annual mean



- The MISR AOD observation for the last 18 years and its temporal subset may provide enough information to examine global mean optical depths for different types of aerosols and possibly, their radiative forcing with quantitative uncertainties.
- However, the stability varies considerably by locations even for the annual mean AOD climatology.

The seasonal cycle of simulated AOD (March 2000 – February 2005)



- In East China, the observed total AOD peaks in spring whereas the nonabsorbing AOD is highest in summer. Only GOCART simulation reproduced these observed seasonal cycles.
- In the west of the Sahara Desert, both total and non-spherical AOD peak in summer. This seasonal cycle is well represented in all three models.

Summary: part II

- The length of satellite observation records affect the climatological aerosol optical depth (AOD), especially the multi-year mean of optical depth by components.

- At a global scale, the climatological AOD defined using more than 10 years of MISR data is stable.

- However, the large uncertainty of climatological mean AOD in some regions indicates that we do need longer observations to obtain reliable AOD climatology by components.

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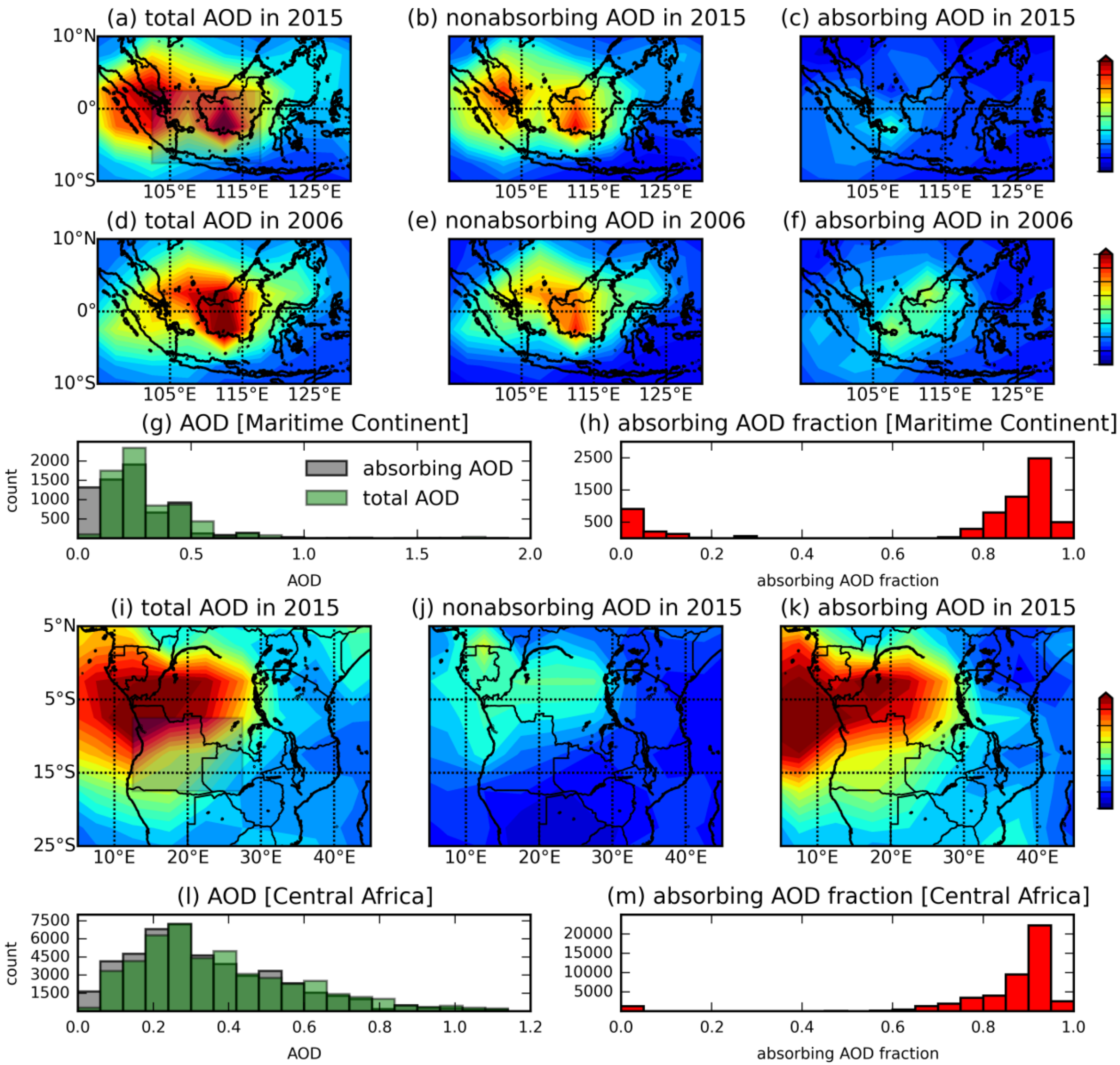
- **Optical properties of wildfire-induced aerosols**
  - *Huikyo Lee, Su-Jong Jeong, Olga Kalashnikova, Mika Tosca, Sang-Woo Kim, and Jong-Seong Kug* (2018), Characterization of wildfire-induced aerosol emissions from the Maritime Continent peatland and Central African dry savannah with MISR and CALIPSO aerosol products, JGR.
- AirMSPI and MAIA: towards the aerosol observation of the future

Motivation

- The strong El Niño related wildfire over Indonesia between late June and October in 2015 emitted about 1.35 Gt of CO_2 equivalents (almost same as the total emission from Japan).
- The wildfire also became a massive source of aerosols. Multiple countries suffered from the fire related smog.
- The burned area's soil is abundant in **peat**. Peat is partially decayed vegetation or organic matter and highly combustible during dry season.
- Can we use satellite observations to characterize optical properties of the aerosols from 2015 Indonesia Fire?

types of vegetation and soil → smoke composition → **Optical properties of aerosols**

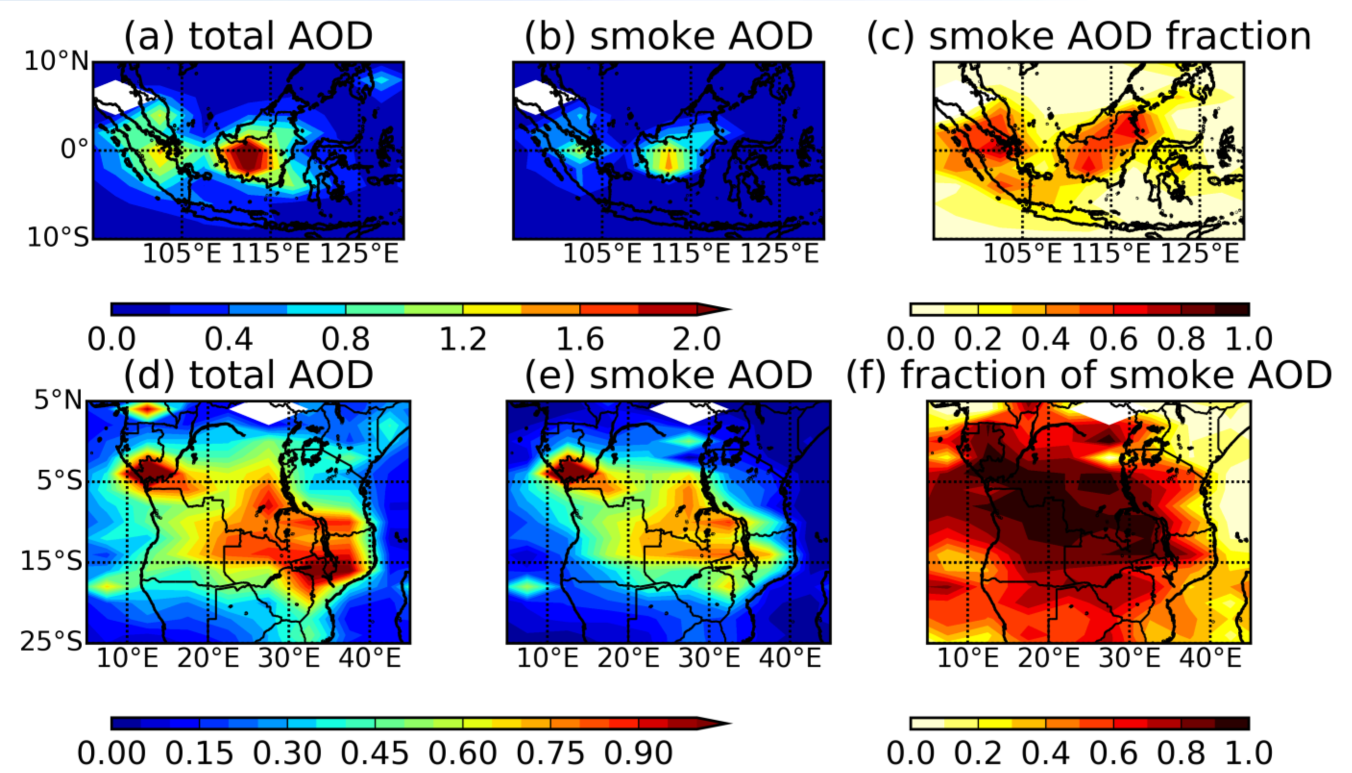
Comparison of aerosol types in MISR between the Maritime Continent and Central Africa



- The aerosol optical properties retrieved from satellite-based observations with consistent retrieval for years enable investigation of the aerosol characteristics reflecting terrestrial environments (burning conditions).

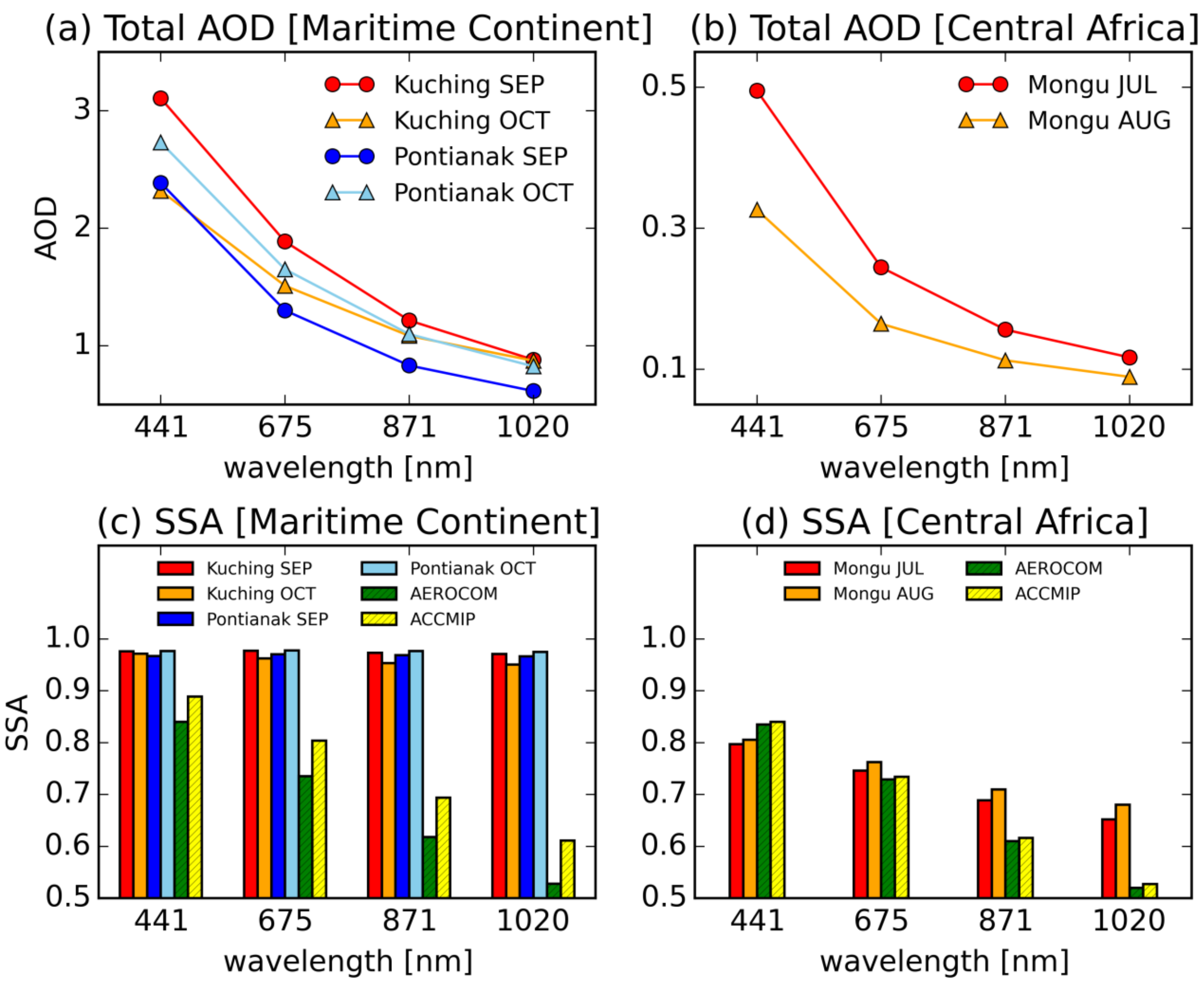
- The absorbing aerosols account for a significantly lower fraction in smoke plumes from the Maritime Continent than those from Central Africa.

Comparison of aerosol types in the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)



- The lower fraction of smoke AOD over the Maritime Continent compared to Central Africa is consistent with the MISR observation.

AERONET measurements and optics simulations



- The smoke plumes from wildfires in the Maritime Continent reflect shortwave radiation more efficiently than those in Central Africa.

- Idealized simulations of SSA using the ratios of black carbon aerosol fluxes used for AEROCOM and ACCMIP: The calculated SSA for Central Africa is comparable to the observations, whereas the observed SSA is much larger than simulated SSA in the Maritime Continent.

Summary: part III

- The absorbing aerosols account for a significantly lower fraction in smoke plumes from the Maritime Continent than those from Central Africa.
- The wildfire-aerosol-climate feedback processes largely depend on the terrestrial environment sand fire-burning conditions (Maritime Continent peatland vs. Central African dry savannah).
- The optical properties of carbonaceous aerosol mixtures used by AEROCOM models may overestimate emissions for absorbing aerosols from wildfires over the Maritime Continent.

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A decadal (2018-2027) strategy for Earth Observation from Space by the National Academies of Sciences

Recommended NASA Priorities: Designated

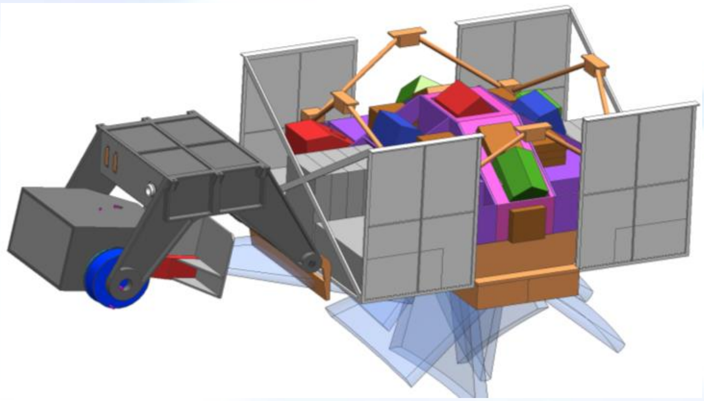
http://sites.nationalacademies.org/cs/groups/depssite/documents/webpage/deps_183919.pdf

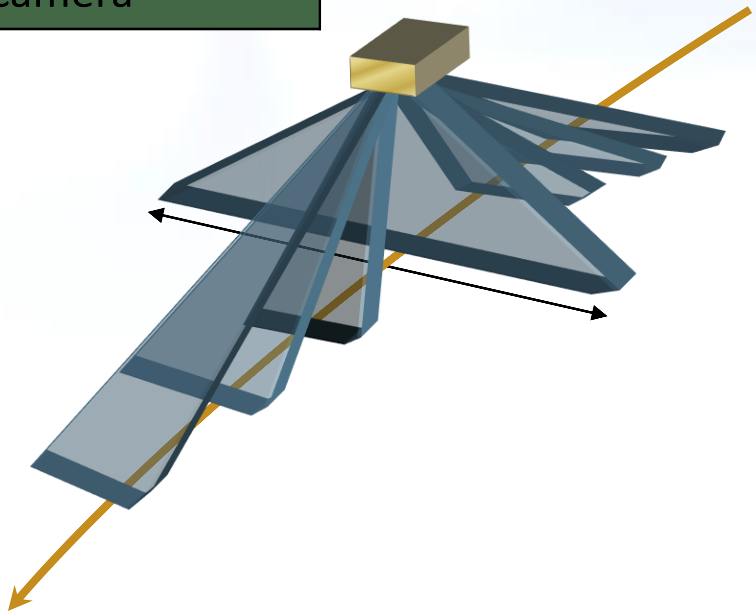
TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Aerosols	**Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their direct and indirect effects on climate and air quality	Backscatter lidar and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, & Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	X		
Mass Change	**Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology & Geology	**Earth surface geology and biology,** ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation & Change	**Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		

- Three tiers in the recommended NASA priorities: Designated > Explorer > Incubation

Multiangle SpectroPolarimetric Imager (MSPI)

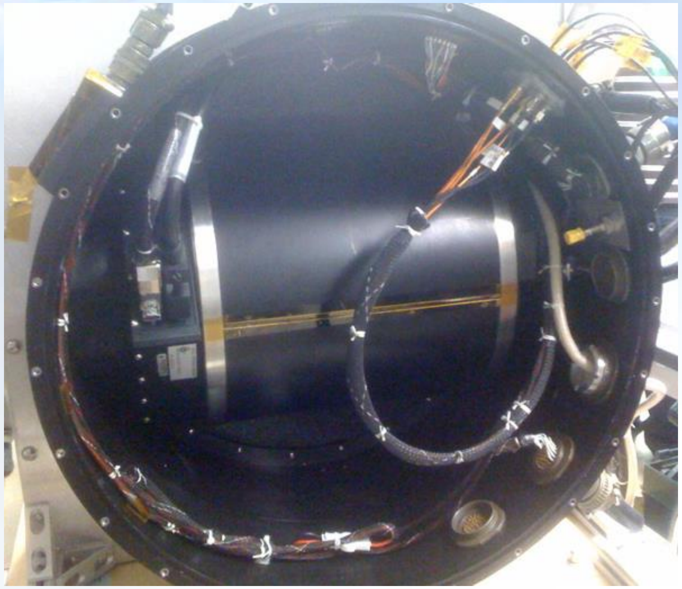
MISR	MSPI
9 cameras, 4 VNIR bands	9 cameras, UV-VNIR-SWIR bands Polarimetry in selected bands
View angles (9): Nadir, 26º, 46º, 60º, 70º	Fixed view angles (7): Nadir, 38º, 60º, 70º + gimbaled camera

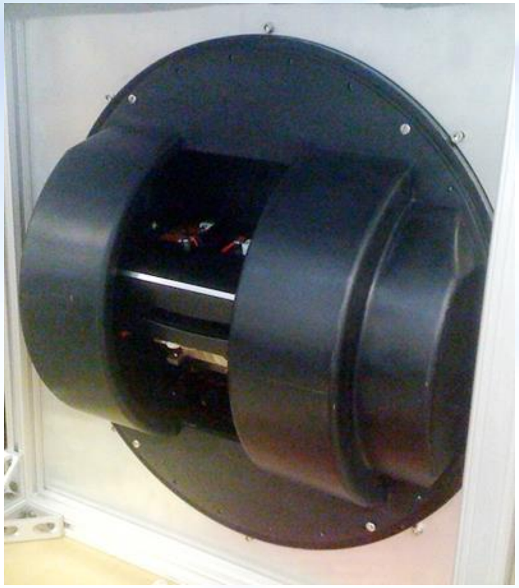




courtesy of Michael Garay at JPL

Airborne Multiangle SpectroPolarimetric Imager (AirMSPI)





Spectral bands: 355, 380, 445, 470*, 555, 660*, 865*, 935 nm (*polarimetric)

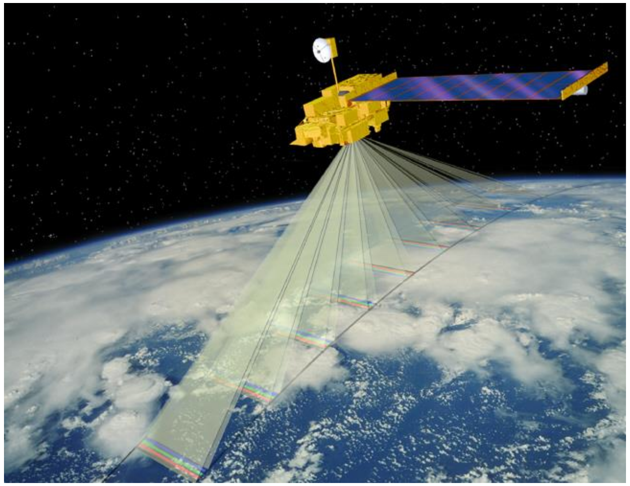
Flies in nose of NASA ER-2

Has flown: Oct 2010, Aug/Sep 2011, Jan 2012, Jul/Aug 2012, Jan/Feb 2013 (PODEX), May 2013, Aug/Sept 2013 (SEAC^{4}RS), Oct 2013

courtesy of Michael Garay at JPL

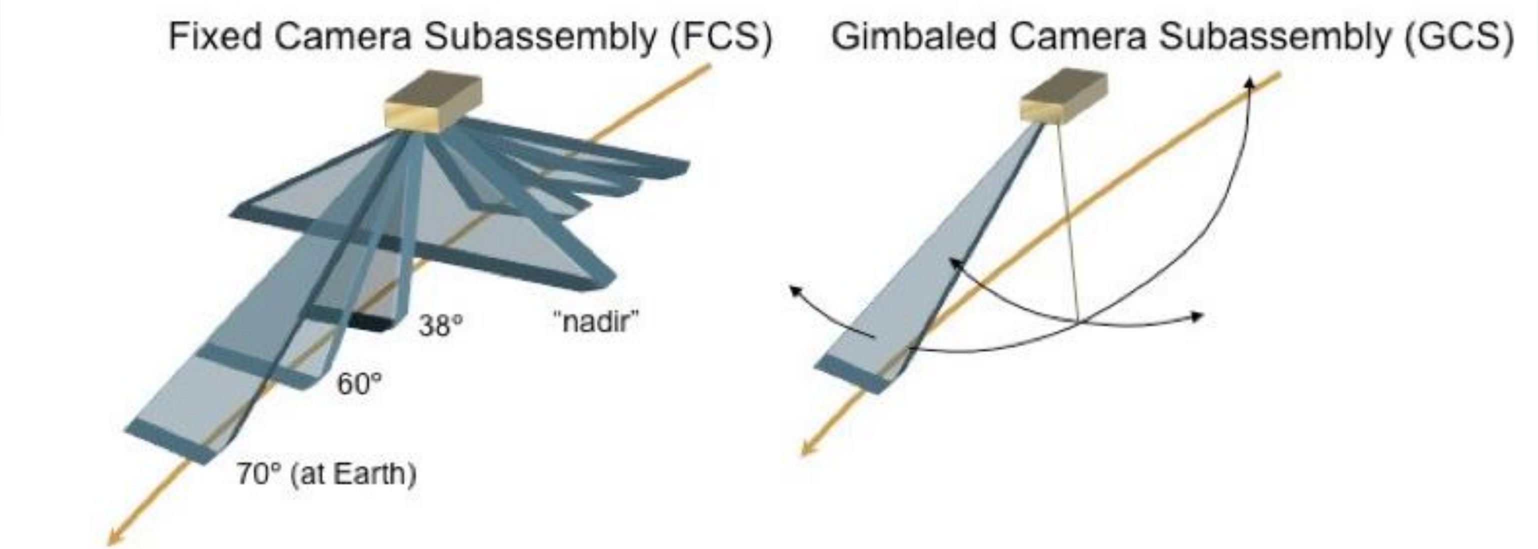
Evolution from MISR to AirMSPI

Capability	Purpose	MISR	AirMSPI
UV bands	Aerosol height, aerosol absorption	Not included	365, 380 nm
VNIR bands	Fine mode aerosols, land and ocean surface	446, 558, 672, 866 nm	445, 470*, 555, 660*, 865*, 935 nm
SWIR bands	Coarse mode aerosol, clouds, atmospheric correction	Not included	Not included
Multiangle views	Aerosols, albedo, texture	0º-70º views, 9 angles	0º-70º views with gimbaled camera
Polarimetry	Aerosol refractive index, surface texture and orientation	Not included	0.5% DOLP tolerance
Spatial resolution	Scene classification, stereo	275 m – 1.1 km	10 m – 25 m



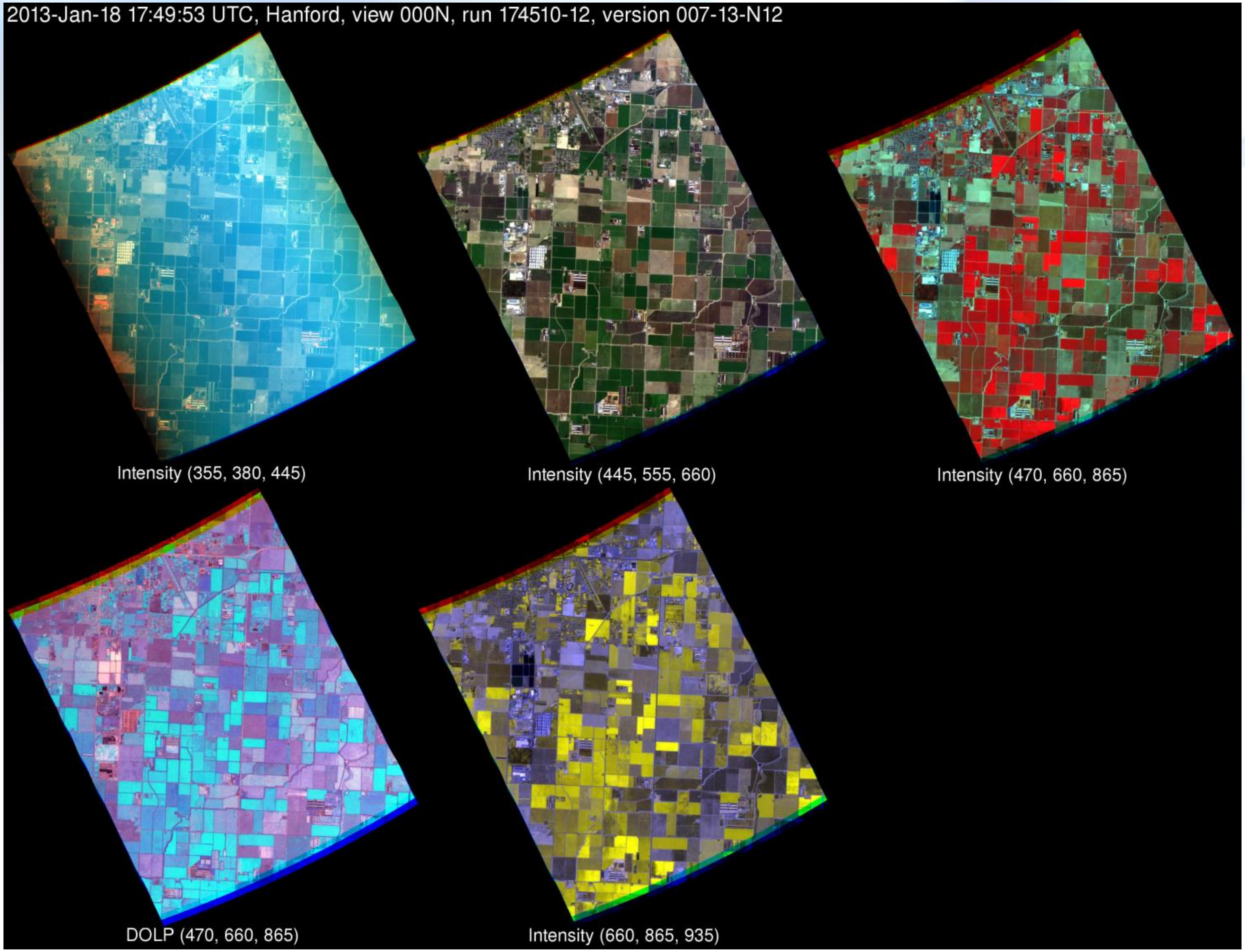
courtesy of Michael Garay at JPL

Example Sampling Strategy



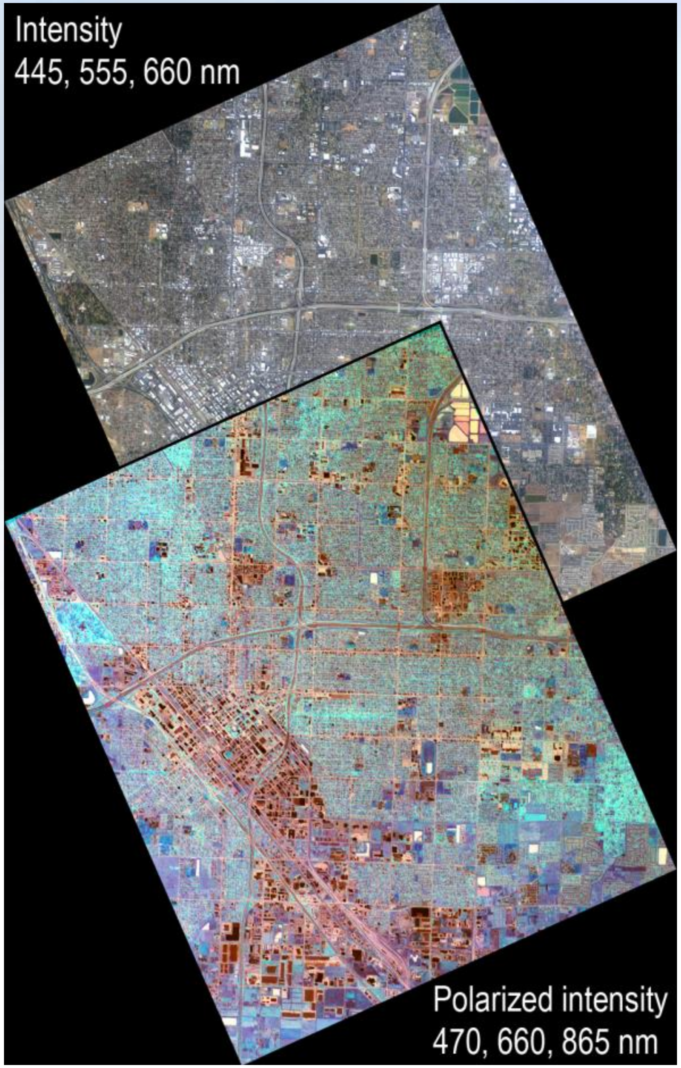
courtesy of Michael Garay at JPL

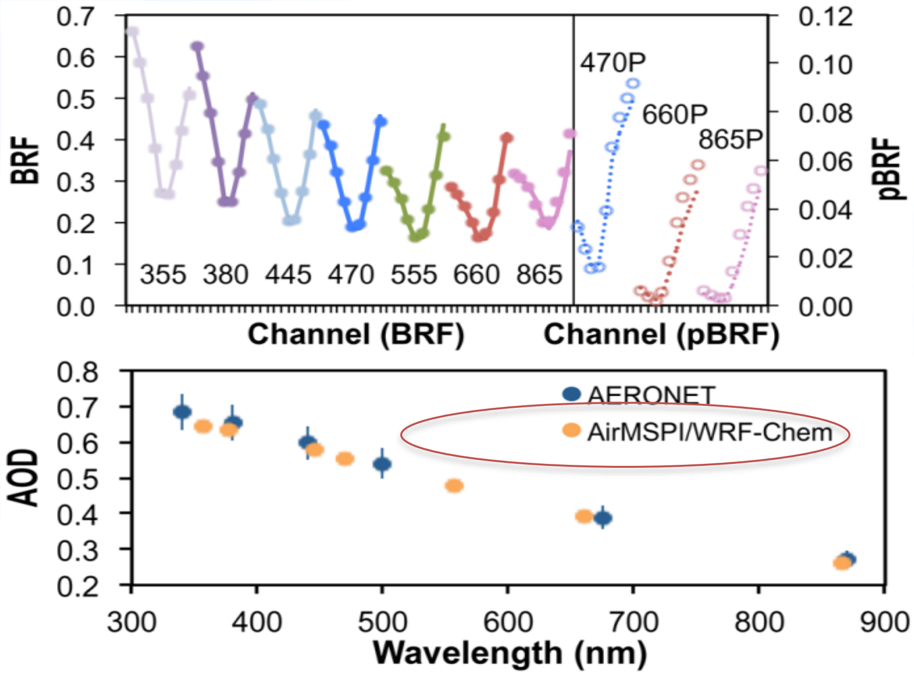
Multispectral nadir imagery over Hanford, CA on 18 Jan. 2013



courtesy of Michael Garay at JPL

Strength of AirMSPI is its high resolution and UV + polarimetric imagery which enhance particle sensitivity





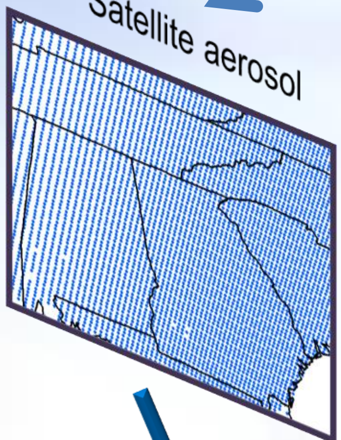
AirMSPI observations over Fresno, January 2012

courtesy of Michael Garay at JPL

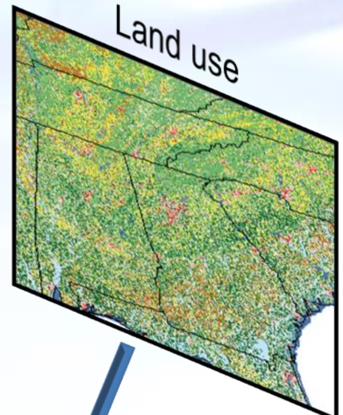
An *integrated* approach, combining satellites, air quality models, and surface monitors is essential

Chemical transport model provides aerosol vertical profiles to get the boundary layer fraction of total AOD.

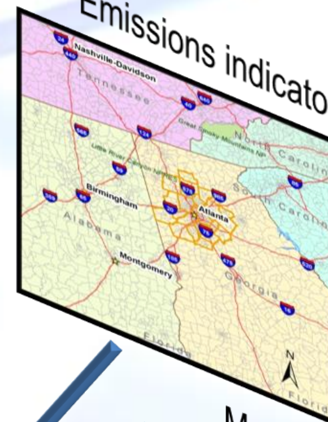
Satellite aerosol



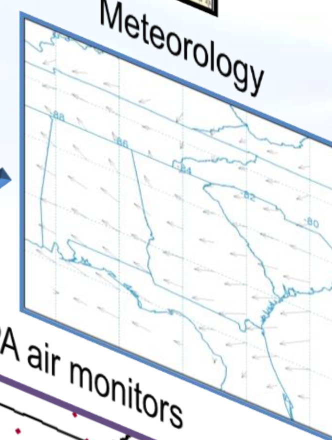
Land use



Emissions indicators



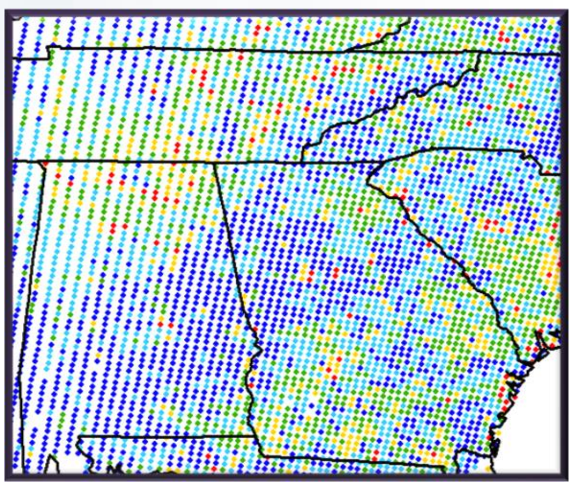
Meteorology



EPA air monitors

Satellite data, meteorology, land use, emissions indicators (e.g., population, traffic information), and EPA measurements are used as inputs to develop a statistical model to predict $PM_{2.5}$ concentration.

Spatial statistical model



Predicted $PM_{2.5}$

Existing EPA surface stations are necessary for establishing accurate mappings of satellite data to PM.

courtesy of Michael Garay at JPL

The decision to implement MAIA will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

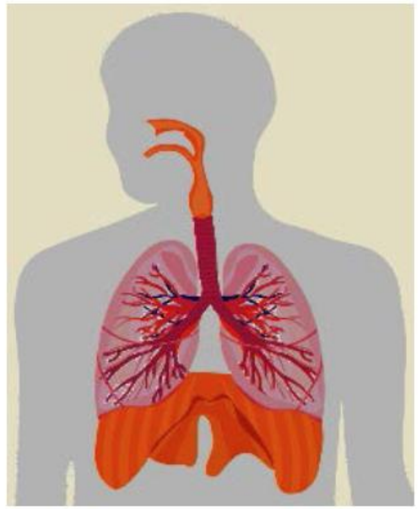
MAIA

Associating airborne particle types with adverse health outcomes

Multi-Angle Imager for Aerosols (MAIA)

The following slides are provided by MAIA PI:
David Diner
JPL

MAIA objective



Coarse particles irritate and inflame our respiratory systems.

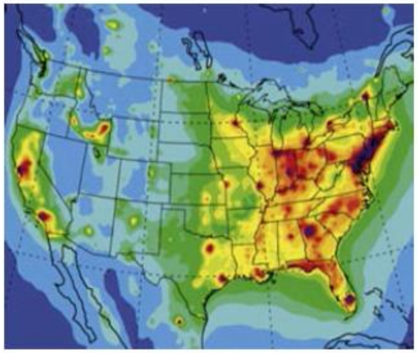
Fine particles penetrate deep into our lungs and carry toxins into our bloodstreams.

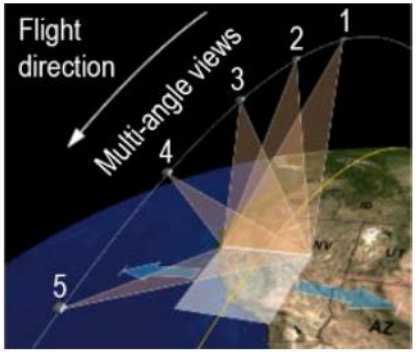
Airborne **particulate matter (PM)** is a well-known cause of cardiovascular and respiratory diseases, heart attacks, low birth weight, lung cancer, and premature death.

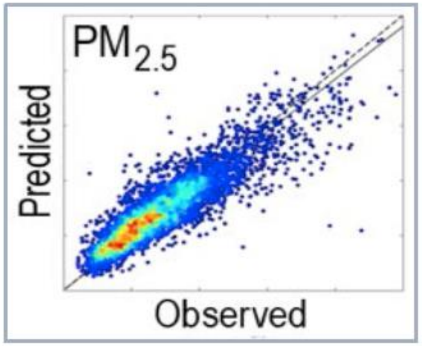
But the relative toxicity of specific **PM types** is poorly understood.

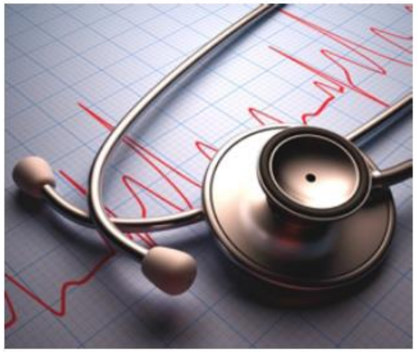
MAIA is designed to fill this gap in our understanding and enable more cost-effective pollution controls and improved health outcomes.

MAIA investigation approach









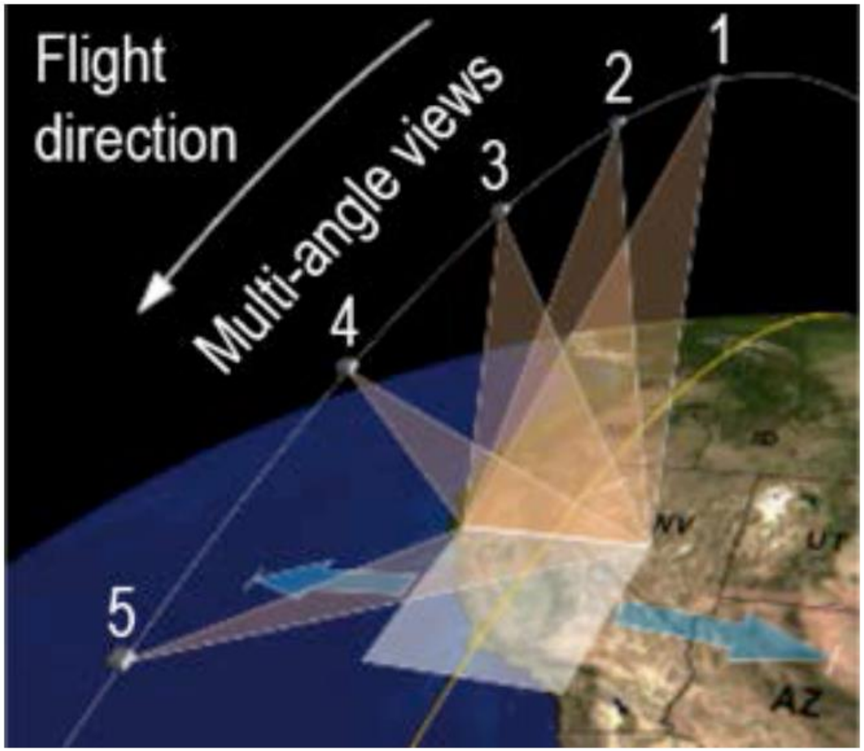
The WRF-Chem chemical transport model (CTM) provides initial estimates of the abundances of different aerosol types, along with their vertical distributions.

The MAIA instrument uses multi-angle and multispectral radiometry and polarimetry to eliminate CTM biases and retrieve fractional aerosol optical depths of different particle types.

Geostatistical models (GSMs) derived from collocated surface and MAIA measurements relate fractional aerosol optical depths to near-surface concen-trations of major PM constituents.

Geocoded birth, death, and hospital records and epidemiological methodologies are used to associate PM exposure with adverse health outcomes.

MAIA cameras are mounted on a 2-axis gimbal for targeted science operations and calibration



Along-track axis provides step-and-stare multiangle imagery (±60º at instrument)

Cross-track axis proves axis to targets off the sub-satellite track (±45º at instrument)